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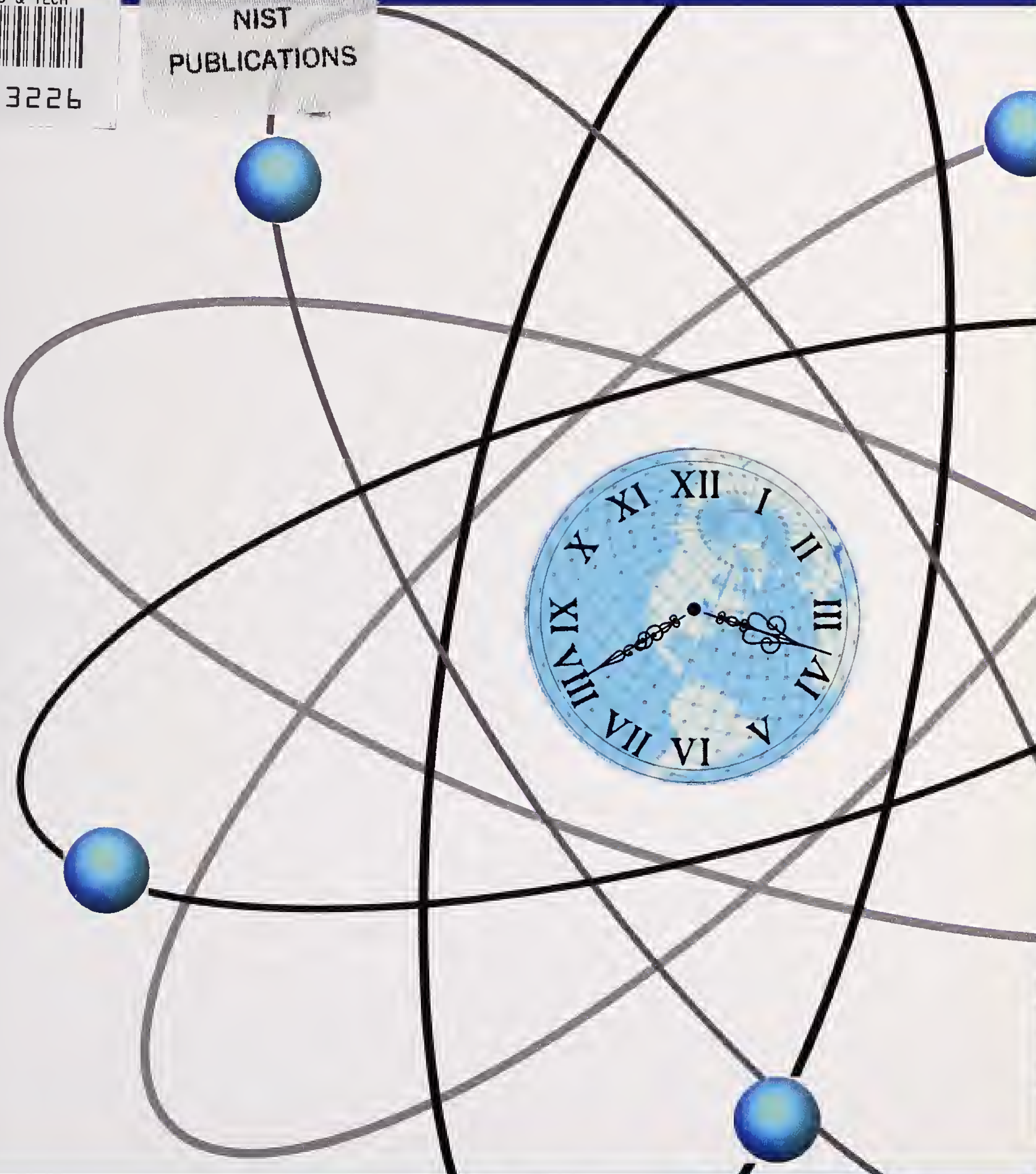
NIST Time and Frequency Services

Michael A. Lombardi



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NIST Time and Frequency Services

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Chapter 1

How NIST Provides Time and Frequency Standards for the United States

The National Institute of Standards and Technology (NIST) maintains the standards for time and frequency for most users in the United States. NIST provides a variety of services designed to deliver time and frequency signals to the people who need them. The signals are broadcast via several mediums, including high and low frequency radio, the Internet, and telephone lines. These signals are used to synchronize millions of clocks everyday, throughout the United States and around the world. This booklet is a guide to NIST Time and Frequency Services. It describes the signals and services offered by NIST, how they work, and how you can use them.

Beginning with Chapter 2, we'll take a detailed look at each of the time and frequency services that NIST provides. However, let's begin by discussing why time and frequency services are needed in the first place, and how NIST provides and controls them.

Who Needs Time and Frequency Standards?

Everybody needs time and frequency standards. If we stop and think about it, time and frequency standards are involved in one way or another in just about everything we do.

Time and frequency standards supply us with three basic types of information. The first type, *date and time-of-day*, tell us when something happened. Date and time-of-day can be used to record events, or to make sure that multiple events are *synchronized*, or happen at the same time. It's easy to think of ways we use date and time-of-day in our everyday lives. For example, we use date information to remind us when birthdays, anniversaries, and other holidays are scheduled to occur. We use time-of-day information to set our alarm clocks so we get out of bed on time. Our wristwatches and wall clocks help us get to school and work on time. And if we plan to meet a friend for dinner at 6 p.m., that's a simple example of synchronization. If our watches agree, we should both arrive at about the same time.

Date and time-of-day information have other, more sophisticated uses as well. Fighter planes flying in a high-speed formation require synchronized clocks. If one banks or turns at the wrong time, it could result in a collision and loss of life. If you are watching a network television program, the local station has to be ready to receive the network feed (usually from a satellite), at the exact instant it arrives. This requires synchronization of the station and network clocks. The instruments used to detect and measure earthquakes, called seismographs, require synchronized clocks so that

data collected at various locations can be compared and combined. Stock market transactions need to be synchronized so that the buyer and seller can agree upon the same price at the same time. A time error of just a few seconds could result in a large difference in the price of a stock. The electric power companies also need time synchronization. They use synchronized clocks throughout their power grids, so they can instantly transfer power to the parts of the grid where it is needed most. They also use synchronized clocks to determine the location of short circuit faults along a transmission line.

The second type of information, *time interval*, tells us "how long" it takes for something to happen. We use time interval to state our age, or the amount of time we have been alive. Most workers are paid for the amount of time that they worked, usually measured in hours, weeks, or months. We pay for time as well—30 minutes on a parking meter, a 20 minute cab ride, a 5 minute long distance phone call, or a 30 second radio advertising spot.

The standard unit of time interval is the second (s), which is defined according to a property of the cesium atom, as we shall see shortly. However, many applications in science and technology require the measurement of intervals much shorter than one second; such as *milliseconds* (10^{-3} s), *microseconds* (10^{-6} s), *nanoseconds* (10^{-9} s), and even *picoseconds* (10^{-12} s).

The third type of information, *frequency*, is the rate at which something happens. The unit we use to measure frequency is the hertz (Hz), or the number of events per second. Many of the frequencies we depend upon are generated by fast moving electrical signals that are reproduced many thousands (kHz) or millions (MHz) of times per second, or even faster. For example, the quartz watch on your wrist keeps time by counting the frequency of a quartz crystal designed to run at a frequency of 32,768 Hz. When the crystal has oscillated 32,768 times, the watch records that one second has elapsed. Channel 7 on your television receives video at a frequency of 175.25 MHz. The station has to transmit on this frequency as accurately as possible, so that its signal does not interfere with the signals from other stations. Your television has to be able to pick out the channel 7 frequency from all the other available radio signals, so that you see the correct picture on your screen. A high speed Internet connection might use something called a T1 line, which sends data at a frequency of 1,544,000 bits per second (1.544 MHz). And the computer that you use to connect to the Internet might run at a frequency faster than 1 GHz (one billion cycles per second). All of these applications require an *oscillator* that produces a specific frequency. This oscillator should be *stable*, which means that the frequency it produces stays the same (with only minor variations) over long time intervals.

Accurate frequency is critical to today's communication networks. It shouldn't surprise you that the highest capacity networks run at the highest frequencies. In order to send data faster and faster, we need stable oscillators situated throughout a network that all produce nearly the same frequency. The process of making multiple oscillators run at the same frequency is called *syntonization*.

Of course, all three types of time and frequency information are very closely related. As we mentioned, the standard unit of time interval is the second. If we count seconds in an agreed upon fashion, we can calculate the date and the time-of-day. And if we count the number of events that occur during a second, we can measure the frequency.

It's easy to see that the world depends heavily on time and frequency information, and that we rely on many millions of clocks and oscillators to keep time and produce frequency. To keep the world running smoothly, these devices need to be periodically compared to an internationally recognized standard. This comparison might be as simple as setting our watch or alarm clock to the correct minute, or adjusting the frequency of an atomic oscillator so it keeps time within a few nanoseconds per day. The time and frequency standards maintained by NIST provide the reference for these comparisons.

NIST and the Primary Standards of Measurement

The task of maintaining the national standards for time and frequency is an important part of the work done at NIST, and it fits in perfectly with the agency's mission. NIST serves as the national measurement laboratory, or the ultimate reference point for measurements made in the United States. NIST is responsible for maintaining the seven base physical quantities at the highest possible accuracies. Time is one of the seven base quantities; the others are used in the measurement of length, light, electricity, chemical concentration, temperature, and mass. NIST distributes the standard units of measurement throughout the country in the form of measurement services and standard reference materials. By doing so, it provides measurement references to anyone

Figure 1.1. The NIST Boulder Laboratories

who needs them. If a measurement is made using a NIST reference, and if the uncertainty of the measurement is known and documented, the measurement is said to be *traceable*. Establishing *traceability* is important to many organizations, because it helps them prove that their measurements are being made correctly. In some cases, traceability is even a legal or contractual requirement.

NIST strives to develop in-house measurement capabilities that exceed the highest requirements of users in the United States. Since these requirements become more demanding every year, NIST scientists and researchers are continually developing new standards and measurement techniques to keep up with this demand. While these new standards are being developed, other NIST personnel are busy distributing the existing standards and measurement techniques, so that everyone can make traceable measurements that are nearly as good as those made inside the national laboratory.

Although most of NIST is located in Gaithersburg, Maryland, the Time and Frequency division is located in Boulder, Colorado (Figure 1.1). The time and frequency services controlled from Boulder are excellent examples of how NIST is able to distribute its standards and measurement capability to a wide variety of users throughout the United States.

Atomic Time and the Definition of the Second

We mentioned earlier that the standard unit for time interval is the second (s). Since 1967, the second has been defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the *cesium atom*. Frequency (expressed in hertz) is obtained by counting events over a 1 s interval.

The second is one of the seven base units of measurement in the International System of Units (SI). These units are used to express the values of the seven physical quantities that we mentioned earlier. The seven base units were defined by international agreement and all other units of measurement can be derived from them. The International Bureau of Weights and Measures (BIPM) located near Paris, France, is responsible for ensuring that the major countries of the world use the SI units. This means that the second and the other base units are defined the same way all over the world. As a result, the timekeeping standards maintained by the major countries tend to closely agree with each other—typically to within one microsecond, and often to within a few nanoseconds.

Since the second is defined based on a property of the cesium atom, it should come as no surprise that the electronic device that produces the standard second is called a *cesium oscillator*. Cesium oscillators (and other types of atomic oscillators) are called *intrinsic standards*, because they produce frequency based on a natural phenomena, in this case a property of an atom. NIST maintains an *ensemble* of atomic oscillators in Boulder, Colorado. The outputs of these oscillators are averaged together to produce the national standard for time and frequency. Most of the oscillators in the ensemble are commercially available, but the primary standard, called NIST-F1, is a custom device that was designed and built at NIST (Figure 1.2). The *primary standard* is used to help calibrate the ensemble.

NIST-F1 became operational in late 1999, and is the latest in a long line of NIST primary time and frequency standards. NIST-F1 is a *cesium fountain* frequency standard, and has many performance advantages over the earlier *cesium beam* standards. At this writing (2001), NIST-F1 is one of the most accurate clocks in the world, and can keep time to within about 0.1 nanoseconds per day. Along with the other atomic clocks in the ensemble, NIST-F1 provides the reference for the NIST time and frequency services.

Coordinated Universal Time (UTC)

The ensemble and primary standard described above form what is known as the NIST *time scale*. This time scale produces a very stable and accurate frequency by using a weighted average of all its oscillators, with the best oscillators receiving the most weight. Small adjustments, never more than about 2 nanoseconds per day, are made to the NIST time scale to keep it in agreement with international standards. The output of the time scale is called UTC(NIST), which is short for Coordinated Universal Time kept at NIST.

You can think of UTC(NIST) as both a frequency and a time standard. It produces an extremely stable frequency that serves as the standard for the United States. It also produces the standard for time interval, by generating pulses that occur once per second. By counting these second pulses, NIST can keep time. The second pulses are added together to keep track of longer units of time interval—such as years, months, days, hours, and minutes.

Figure 1.2. NIST-F1 Primary Standard

The UTC system of timekeeping is similar to your local time, with two major differences. Since UTC is used internationally, it ignores local conventions such as Daylight Saving Time and time zones. In other words, UTC is the same no matter where you are located on Earth. Unlike local time, which is usually based on a 12-hour clock, UTC is a 24-hour clock system. The hours are numbered from 0 to 23. The time at midnight is 0 hours, 0 minutes, and 0 seconds. The time just before the next midnight is 23 hours, 59 minutes, and 59 seconds.

To convert UTC to local time, you need to add or subtract a specific number of hours. The number of hours to add or subtract depends on the number of time zones between your location and the zero meridian that passes through Greenwich, England. When local time changes from Daylight Saving to

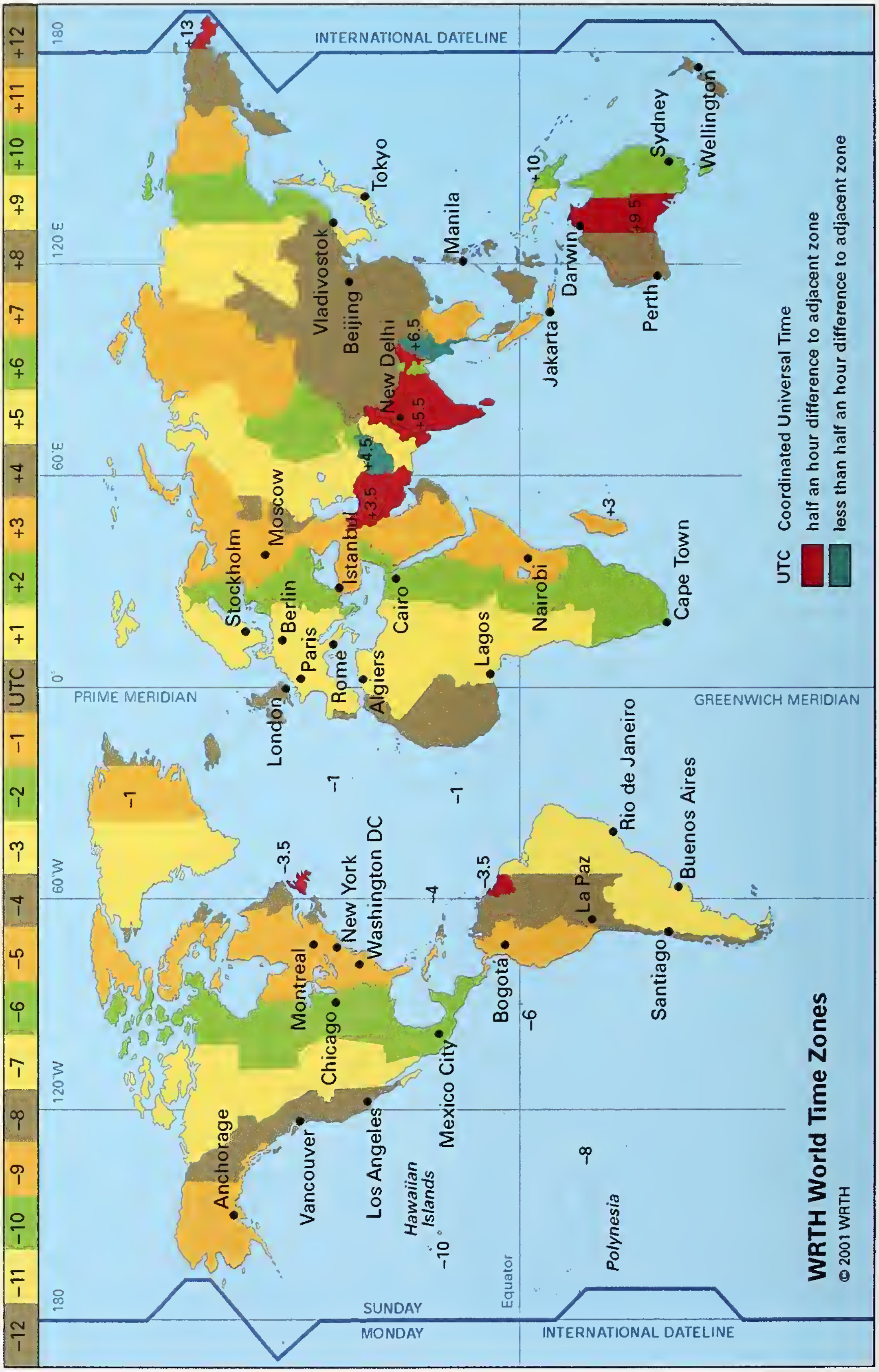

Figure 1.3. World Time Zone Map

Standard Time, or vice versa, UTC does not change. However, the difference between UTC and local time changes by 1 hour. For example, in New York City, the difference between UTC and local time is 5 hours when Standard Time is in effect, and 4 hours when Daylight Saving Time is in effect.

Most of the hardware and software products that access NIST services allow you to select your time zone and are capable of automatically converting UTC to your local time. These products also automatically correct for Daylight Saving Time. The conversion is fairly simple. The chart of world time zones in Figure 1.3 shows the number of hours to add or subtract from UTC to obtain your local standard time. If Daylight Saving Time is in effect at your location, add 1 hour to what is shown on the chart.

Leap Seconds

As we mentioned earlier, the second is defined according to the intrinsic properties of the cesium atom. This means that UTC is an *atomic time scale*, which runs at an almost perfectly constant rate. Prior to atomic time, time was kept using *astronomical time scales* that used the rotation of the Earth as their reference. When the switch to atomic time keeping occurred, it became obvious that while much was gained, some things were lost. A few people still needed time referenced to the Earth's rotation for applications such as celestial navigation, satellite observations of the Earth, and some types of surveying. These applications relied on an astronomical time scale named UT1.

For these reasons, it was agreed that UTC should never differ from UT1 by more than 0.9 s. Therefore, those who needed UT1 could just use UTC, since they could be sure that the difference between the two time scales would be less than 1 s. Keeping the two time scales in agreement requires making occasional 1 s adjustments to UTC. These adjustments are called *leap seconds*. A leap second can be positive or negative, but so far, only positive leap seconds have been needed. Leap seconds are announced by the International Earth Rotation Service and are usually inserted into the UTC time scale on June 30 or December 31, making those months 1 s longer than usual. Currently, about 4 leap seconds are required every 5 years.

All NIST services automatically add leap seconds when necessary. For the very few people who need to know UT1 with an uncertainty of less than 1 s, most NIST services also broadcast a UT1 *correction*. This correction reports the current time difference between UTC and UT1 to the nearest 0.1 s.

Traceability

Earlier, we introduced the concept of measurement traceability. Each of the NIST time and frequency services provides a way to establish traceability to NIST and to international standards. You can think of traceability as a chain that extends all the way from the definition of the SI unit to your measurement or application. Keeping the chain intact requires making a series of comparisons. Each link in the chain is continually compared to the previous link. Figure 1.4 illustrates the part of the traceability chain that extends from the SI definition of the second down to the NIST services.

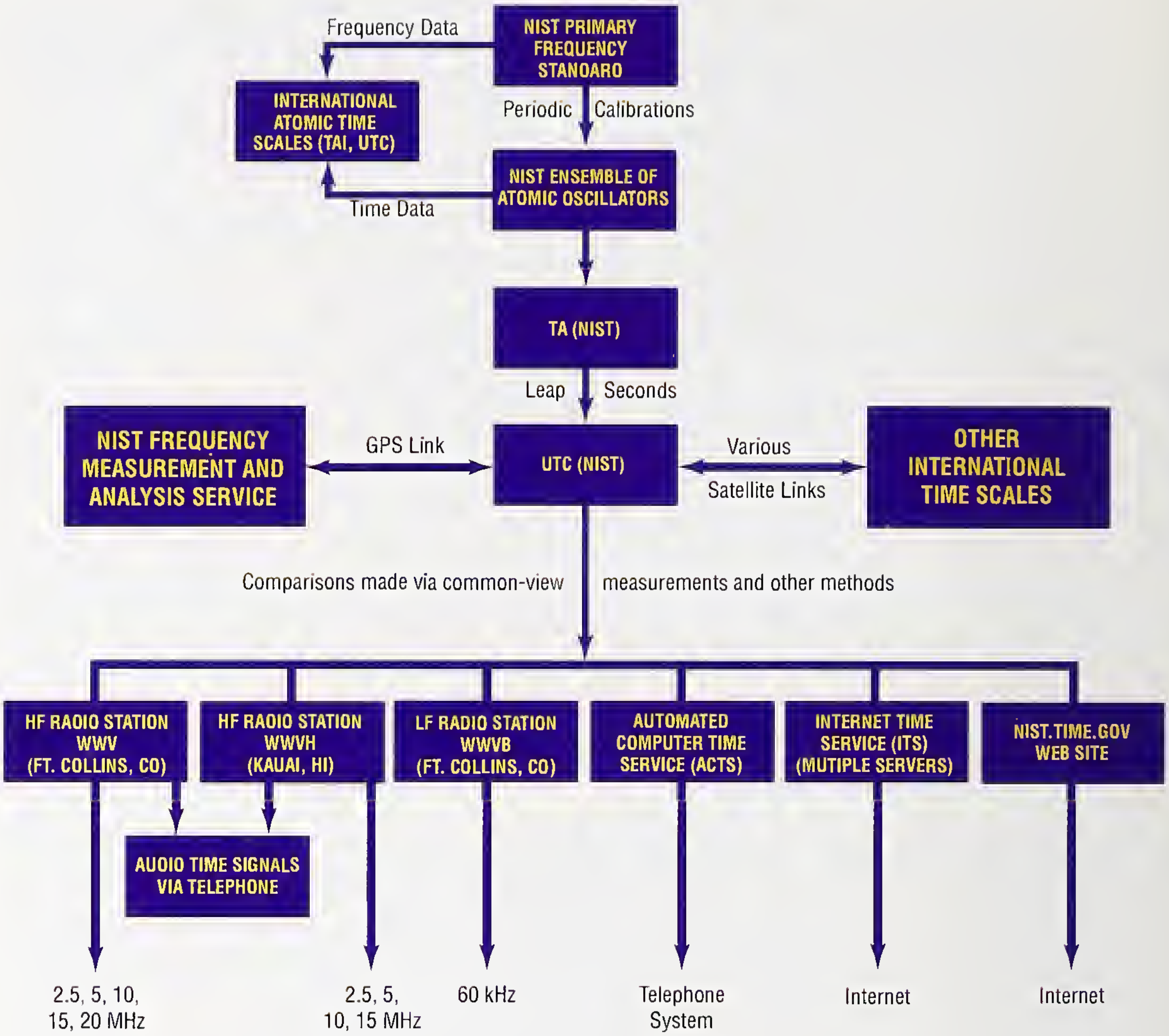

Figure 1.4. The Traceability Chain for NIST Time and Frequency Services

The traceability chain starts with a time and frequency source that is as nearly perfect as possible. For example, at the NIST laboratories it is possible to synchronize a clock to within nanoseconds or even picoseconds of UTC. However, as we transfer UTC down through the links in the chain, we add *uncertainty* to our measurement. By the time a NIST service is used to synchronize a computer clock, the time might only be within a few milliseconds of UTC, and these few milliseconds become our *measurement uncertainty* relative to UTC. This is an important concept. Whenever we talk about traceability, we also need to talk about measurement uncertainty. The typical uncertainty of each time and frequency service is discussed in the following chapters.

Let's cxamine Figure 1.4 to see how the traceability chain works. We mentioned that NIST compares its time and frequency standards to the time scales maintained in other countries. The comparison data are handled and processed by the BIPM, the same organization responsible for the SI units. Most international comparisons are done using

a technique called *common-view*. Normally, if you wanted to compare one oscillator or clock to another, you would connect them both to the same measurement system and make a comparison. However, what if the two clocks aren't located in the same place? They might be in different buildings, different cities, or even different countries. For example, what if you want to compare a clock in the United States to one in Italy? Obviously, you can't directly compare them using the same measurement system, but you can indirectly compare them using the common-view technique.

To use the common-view technique, both oscillators are simultaneously compared to a common-view reference and measurement data are collected. The reference is usually a Global Positioning System (GPS) satellite, although other satellite and land based signals are sometimes used. The collected measurement data are then exchanged and processed to see how one oscillator compares to the other. For the purposes of illustration, let's say that the clock in the United States is measured to be 10 ns fast with respect to the satellite, and the clock in Italy is measured to be 10 ns slow with respect to the satellite. Even though we were unable to directly compare the two clocks, we now know that the United States clock was 20 ns ahead of the Italian clock at the time the common-view measurement was made.

NIST is one of about 50 laboratories that send their common-view data to the BIPM. Like NIST, most of these laboratories serve as the ultimate reference point for measurements made in their countries. The BIPM averages data from all of the contributing laboratories, and produces a time scale called International Atomic Time (TAI). When corrected for leap seconds, TAI becomes Coordinated Universal Time (UTC), or the true international time scale.

Unlike UTC(NIST) and similar time scales maintained by other laboratories, UTC is a paper time scale. About 250 oscillators contribute to UTC, but the BIPM has access only to the data, not the oscillators. Even so, the BIPM's role is very important. They publish the time offset or difference of each laboratory's version of UTC relative to the international average. For example, the BIPM publishes the time offset between UTC and UTC(NIST), which is typically less than 10 ns. The work of the BIPM makes it possible for NIST and the other laboratories to adjust their standards so that they agree as closely as possible with the rest of the world. Since every national measurement laboratory is always comparing itself to the other laboratories, you can rest assured that the units of time and frequency are defined in the same way all over the world.

The process of comparing the NIST time scale to the other standards of the world completes the first link of the traceability chain. The second link is used to control the broadcast services described in Chapters 2 through 4. These services are continuously compared to the NIST time scale, and much care is taken to keep the measurement uncertainty as small as possible. Some of the services used to synchronize computer equipment (Chapter 4) are directly connected to the NIST time scale, but most are referenced to atomic standards located outside of NIST's Boulder, Colorado, laboratory. For example, the NIST radio station sites described in Chapters 2 and 3 are located in Fort Collins, Colorado, and Kauai, Hawaii. Three cesium standards are kept at Fort Collins and

Kauai to provide the reference for each station's time code generators and transmitters. These standards are continuously compared and adjusted to agree with the Boulder time scale, using the same common-view technique used for the international comparisons. As a result, time can easily be kept within 100 ns of UTC(NIST) at each radio station.

The next link in the traceability chain connects NIST to the user. The signals broadcast by NIST must travel across a path en route to the user, and the uncertainties introduced by this link are much larger than those introduced by the previous two links. As we shall see in the following chapters, signals that travel over a low frequency (LF) radio or satellite path usually have smaller uncertainties than signals that travel over a high frequency (HF) radio path, or a telephone or Internet path.

The final link in the traceability chain occurs when you actually use the signal. Some uncertainty is always added after the signal arrives at your location. The amount of uncertainty added depends upon your application. In some cases, the amount of uncertainty added by this final link will be much larger than the combined uncertainty of all the previous links. For example, if you use a NIST signal to synchronize a computer clock (Chapter 4), the resolution of the clock is one limiting factor. If the clock displays only seconds, you won't be able to synchronize it to less than one second. Another source of uncertainty is the delay introduced by your client software or operating system, which might be larger than the total broadcast delay. If you calibrate a stop watch using an audio time signal (Chapter 3), the largest cause of uncertainty is human reaction time, which is not nearly as stable or consistent as the audio signal. In other cases, the uncertainty of the final link is very small. The best receivers and measurement systems use sophisticated electronics and software to preserve as much of the signal accuracy as possible.

As you read through the rest of this booklet, keep the traceability chain in mind. NIST maintains time and frequency standards that are as nearly perfect as possible. By providing time and frequency services, NIST makes it possible for all of us to use these standards as the reference for our own measurements.

Time and Frequency Services Offered by NIST

Table 1.1 lists the time and frequency services currently offered by NIST. It also lists the medium each service uses to deliver its time and frequency information, what you need to have in order to use the service, and some of its typical applications. The remaining chapters provide a detailed look at each service listed in the table.

For the current status of each of these services, including contact information, broadcast outage reports, and new developments, please visit the NIST Time and Frequency Division web site located at:

http://www.boulder.nist.gov/timefreq

TABLE 1.1 – TIME AND FREQUENCY SERVICES OFFERED BY NIST

NAME OF SERVICE	REQUIREMENTS	CHAPTER	TIME UNCERTAINTY	FREQUENCY UNCERTAINTY
nist.time.gov web site	Computer, Internet connection, web browser	4	< 2 s	Not applicable
Telephone time-of-day service	Telephone	3	< 30 ms	Not applicable
Automated Computer Time Service (ACTS)	Computer, analog modem, telephone line, client software	4	< 15 ms	Not applicable
Internet Time Service (ITS)	Computer, Internet connection, client software	4	< 100 ms	Not applicable
Radio Stations WWV and WWVH	HF receiver	3	1 to 20 ms	10^{-6} to 10^{-9}
Radio Station WWVB	LF receiver	2	0.1 to 15 ms	10^{-10} to 10^{-12}
Frequency Measurement Service (FMS)	Paid subscription, NIST provides equipment	5	< 20 ns	2×10^{-13}

Chapter 2

Synchronizing the Nation's Clocks: NIST Radio Station WWVB

There are literally millions of wall clocks, desk clocks, clock radios, wristwatches, and other devices that set themselves to NIST time. These *radio controlled clocks* contain tiny radio receivers tuned to NIST radio station WWVB, located near Fort Collins, Colorado. WWVB continuously broadcasts time and frequency signals at 60 kHz, in the part of the radio spectrum known as low frequency (LF). The WWVB signal includes a time code containing all of the information needed to synchronize radio controlled clocks in the United States and the surrounding areas. In addition, calibration and testing laboratories use the 60 kHz carrier frequency from WWVB as a reference for the calibration of electronic equipment and frequency standards.

History of WWVB

LF and VLF (very low frequency) broadcasts have long been used to distribute time and frequency standards. As early as 1904, the United States Naval Observatory (USNO) was broadcasting time signals from the city of Boston as an aid to navigation. This experiment and others like it made it evident that LF and VLF signals could cover a large area using a relatively small amount of power. By 1923, NIST radio station WWV (Chapter 3) had begun broadcasting standard carrier signals to the public on frequencies ranging from 75 to 2000 kHz. These signals were used to calibrate radio equipment, which became increasingly important as more and more stations became operational. Over the years, many radio navigation systems were designed using stable time and frequency signals broadcast on the LF and VLF bands. The most well known of these navigation systems is LORAN-C, which allows ships and planes to navigate by transmitting stable 100 kHz signals from multiple transmitters.

The station known today as WWVB began life as radio station KK2XEI in July 1956. The transmitter was located at Boulder, Colorado, and the radiated power was just 1.4 W. Even so, the signal was monitored at Harvard University in Massachusetts. The purpose of this experimental transmission was to show that the radio path was stable and the frequency error was small at low frequencies.

In 1962, NIST (then called the National Bureau of Standards or NBS) began building a new facility at a site north of Fort Collins, Colorado. This site became the home of WWVB and WWVL, a 20 kHz transmitter that was moved from the mountains west of Boulder.

The site was attractive for several reasons, one being its exceptionally high ground conductivity, which was due to the high alkalinity of the soil. It was also reasonably close to Boulder (about 80 km, 49.3 mi), which made it easy to staff and manage; but much farther away from the mountains. The increased distance from the mountains made it a better choice for broadcasting an omnidirectional signal.

WWVB went on the air on July 5, 1963, broadcasting a 7 kW signal on 60 kHz. WWVL began transmitting a 500 W signal on 20 kHz the following month. Although WWVL went off the air in July 1972, the WWVB signal became a permanent part of the nation's infrastructure.

A time code was added to WWVB on July 1, 1965. This made it possible for radio clocks to be designed that could decode the signal and automatically synchronize themselves. The time code format has changed only slightly since 1965; it uses a scheme known as binary coded decimal (BCD) which uses four binary digits (bits) to send one decimal number.

The radiated power of WWVB was increased to its current level of 50 kW in 1999. The power increase made the coverage area much larger, and made it easy for tiny receivers with simple antennas to receive the signal. This resulted in the introduction of many new low cost radio controlled clocks that "set themselves" to agree with NIST time.

Figure 2.1. Aerial View of WWVB/WWV Station Site

Figure 2.2. WWVB Antenna Towers

WWVB Station Description

WWVB is located on a 390 acre (158 hectare) site located near Fort Collins, Colorado. Radio station WWV (Chapter 3) shares the same location. An aerial view of the station site is shown in Figure 2.1.

WWVB uses two nearly identical antennas that were originally constructed in 1962, and refurbished in 1999. The north antenna was originally built for the now discontinued WWVL 20 kHz broadcast, and the south antenna was built for the WWVB 60 kHz broadcast. The antennas are spaced 867 m apart. Figure 2.2 shows two of the south antenna towers.

Each antenna is a top-loaded dipole consisting of four 122 m (400 ft) towers arranged in a diamond shape (Figure 2.3). A system of cables, often called a capacitance hat or top hat, is suspended between the four towers. This top hat is electrically isolated from the towers, and is electrically connected to a downlead suspended from the center of the top hat. The combination of the downlead and the top hat serves as the radiating element.

Ideally, an efficient antenna system requires a radiating element that is at least one-quarter wavelength long. However, at a low frequency such as 60 kHz, it is difficult to construct an antenna that large. The wavelength of 60 kHz is about 5000 m, so a one-quarter

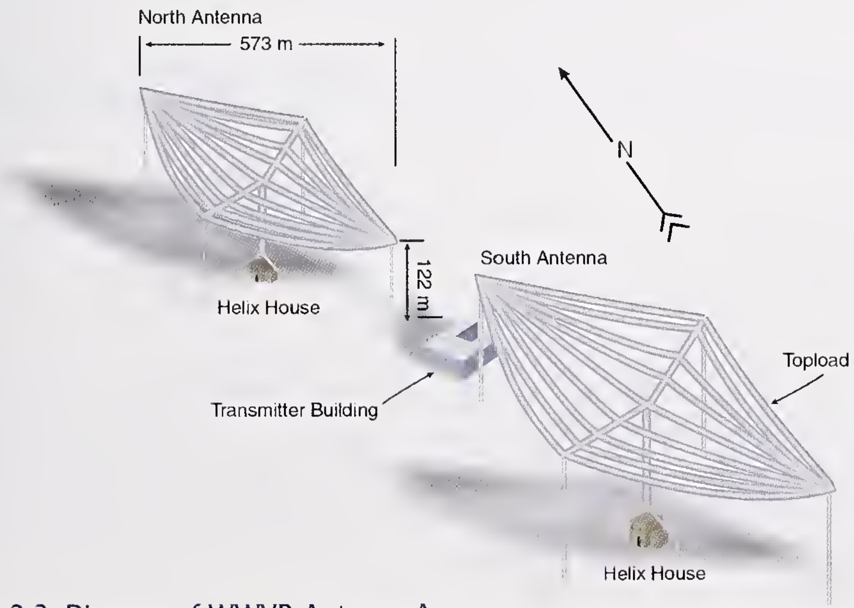

Figure 2.3. Diagram of WWVB Antenna Array

Figure 2.4. A WWVB Transmitter

wavelength antenna would be 1250 m tall, or about 10 times the height of the WWVB antenna towers. As a compromise, some of the missing length was added horizontally to the top hats of this vertical dipole, and the downlead of each antenna is terminated at its own helix house under the top hats. Each helix house contains a large inductor to cancel the capacitance of the short antenna and a variometer (variable inductor) to tune the antenna system. Energy is fed from the transmitters to the helix houses using underground cables housed in two concrete trenches. Each trench is about 435 m long.

A computer is used to automatically tune the antennas during icy and/or windy conditions. This automatic tuning provides a dynamic match between the transmitter and the antenna system. The computer looks for a phase difference between voltage and current at the transmitter. If one is detected, an error signal is sent to a three-phase motor in the helix house that rotates the rotor inside the variometer. This retunes the antenna and restores the match between the antenna and transmitter.

There are three transmitters at the WWVB site. Two are in constant operation and one serves as a standby. A photograph of one of the transmitters is shown in Figure 2.4. Each transmitter consists of two identical power amplifiers that are combined to produce the greatly amplified signal sent to the antenna. One transmitter delivers an amplified time code signal into the north antenna system, and one transmitter feeds the south antenna system. The time code is fed to a console where it passes through a control system and then is delivered to the transmitters.

Using two transmitters and two antennas allows the station to be more efficient than using a single transmitter and antenna. As we described, the length of the WWVB antennas is much less than one-quarter wavelength. And when the length of a vertical radiator is less than the wavelength, the efficiency of the antenna goes down, and some of the transmitter power is lost. In other words, if the efficiency of an antenna is less than 100%, the transmitter power is greater than the effective radiated power. The north antenna system at WWVB has an efficiency of about 57%, and the south antenna has an efficiency of about 59%. However, the combined efficiency of the north and south antennas is about 71%. As a result, each transmitter must produce only about 36 kW of power for WWVB to produce its effective radiated power of 50 kW.

On rare occasions, one of the WWVB antenna systems might require maintenance or repairs. When this happens, the power of one transmitter is temporarily increased to about 50 kW and a single transmitter and antenna are used to deliver the signal. Using this technique, the station is still able to deliver an effective radiated power of about 28 kW.

TABLE 2.1 – CHARACTERISTICS AND SERVICES OF WWVB

CHARACTERISTICS & SERVICES	NIST RADIO STATION WWVB
Date Service Began	July 1956
South Antenna Coordinates	40° 40' 28.3" N 105° 02' 39.5" W
North Antenna Coordinates	40° 40' 51.3" N 105° 03' 00.0" W
Standard Carrier Frequency	60 kHz
Power	50 kW
Standard Time Intervals	Seconds, 10 seconds, minutes
Time of Day Information	Time code frame sent every minute, BCD format

WWVB Signal Description

WWVB identifies itself by advancing its carrier phase 45° at 10 minutes after the hour and returning to normal phase at 15 minutes after the hour. If you plot WWVB phase, this results in an hourly phase shift of approximately 2.1 μs as shown in Figure 2.5.

WWVB is also identified by its unique time code. The time code is synchronized with the 60 kHz carrier and is broadcast continuously at a rate of 1 bit per second using a simple modulation scheme called *pulse width modulation*. The time code is sent in binary coded decimal (BCD) format, where four binary digits (bits) are used to represent one decimal number. The carrier power is reduced and restored to produce the time code bits. The carrier power is reduced 10 dB at the start of each second. If full power is

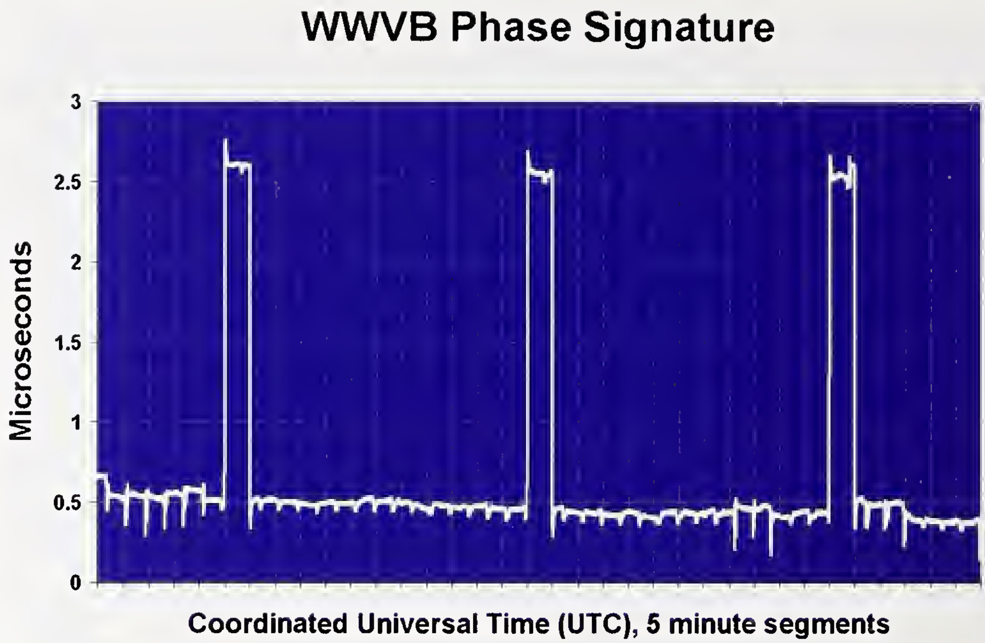

Figure 2.5. WWVB Phase Signature

restored 200 ms later, it represents a 0 bit. If full power is restored 500 ms later, it represents a 1 bit. If full power is restored 800 ms later, it represents a reference marker or a position identifier.

The binary-to-decimal weighting scheme is 8-4-2-1. The *most significant bit* is sent first. This is the reverse of the WWV/ WWVH time code described in Chapter 3. The BCD groups and the equivalent decimal numbers are shown in Table 2.2.

TABLE 2.2 - BCD WEIGHTING SCHEME USED BY WWVB TIME CODE

DECIMAL NUMBER	BIT 1 2^3	BIT 2 2^2	BIT 3 2^1	BIT 4 2^0
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

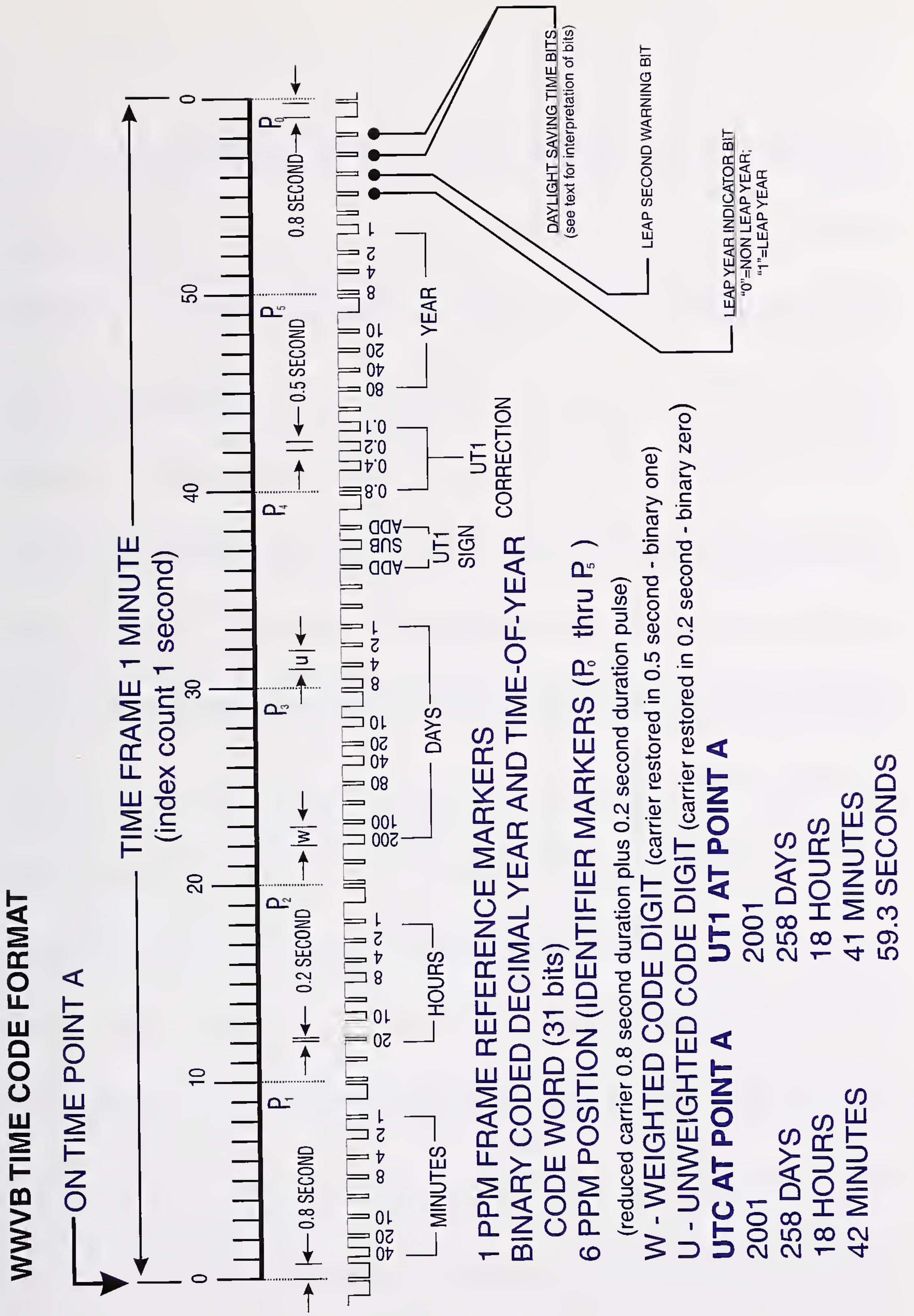

Figure 2.6. The WWVB Time Code Format

TABLE 2.3 - WWVB TIME CODE BITS

BIT NUMBER	BIT DESCRIPTION	BIT NUMBER	BIT DESCRIPTION
0	Frame Reference Bit, P_r	30	Day of Year, 8
1	Minutes, 40	31	Day of Year, 4
2	Minutes, 20	32	Day of Year, 2
3	Minutes, 10	33	Day of Year, 1
4	Reserved	34	Reserved
5	Minutes, 8	35	Reserved
6	Minutes, 4	36	UTI Sign, +
7	Minutes, 2	37	UTI Sign, -
8	Minutes, 1	38	UTI Sign, +
9	Position Marker 1, P_1	39	Position Marker 4, P_4
10	Reserved	40	UT1 Correction, 0.8 s
11	Reserved	41	UT1 Correction, 0.4 s
12	Hours, 20	42	UT1 Correction, 0.2 s
13	Hours, 10	43	UT1 Correction, 0.1 s
14	Reserved	44	Reserved
15	Hours, 8	45	Year, 80
16	Hours, 4	46	Year, 40
17	Hours, 2	47	Year, 20
18	Hours, 1	48	Year, 10
19	Position Marker 2, P_2	49	Position Marker 5, P_5
20	Reserved	50	Year, 8
21	Reserved	51	Year, 4
22	Day of Year, 200	52	Year, 2
23	Day of Year, 100	53	Year, 1
24	Reserved	54	Reserved
25	Day of Year, 80	55	Leap Year Indicator
26	Day of Year, 40	56	Leap Second Warning
27	Day of Year, 20	57	Daylight Saving Time
28	Day of Year, 10	58	Daylight Saving Time
29	Position Marker 3, P_3	59	Frame Reference Bit, P_0

WWVB requires one minute to send its time code (Figure 2.6). The time code frame contains the current minute, hour, day of year, the last two digits of the current year, the UT1 correction, leap year and leap second indicators, and information about daylight and standard time. Two BCD groups are used to express the hour (00 to 23), minute (00 to 59), and year (00 to 99); and three groups are used to express the day of year (001 to 366). The time code frame begins with a frame reference marker consisting of reference bits P_0 and P_r. The on-time reference point of the time code frame is the leading edge of the reference bit P_r. Seconds are determined by counting pulses within the frame. Position markers (P_1 through P_5) lasting for 0.8 s are transmitted every 10 s within the time code frame. The individual bits are annotated in Table 2.3.

UT1 corrections are broadcast at seconds 36 through 43. The bits transmitted at seconds 36, 37, and 38 show if UT1 is positive or negative with respect to UTC. If 1 bits are sent at seconds 36 and 38, the UT1 correction is positive. If a 1 bit is sent at second 37, the UT1 correction is negative. Bits 40, 41, 42, and 43 form a four-bit BCD group that show the magnitude of the correction in units of 0.1 s.

A *leap year* indicator is transmitted at second 55. If it is set to 1, the current year is a leap year. The bit is set to 1 during each leap year after January 1 but before February 29. It is set back to 0 on January 1 of the year following the leap year.

A *leap second* indicator is transmitted at second 56. If this bit is high, it indicates that a leap second will be added to UTC at the end of the current month. The bit is set to 1 near the start of the month in which a leap second is added. It is set to 0 immediately after the leap second insertion.

Daylight saving time (DST) and standard time (ST) information is transmitted at seconds 57 and 58. When ST is in effect, bits 57 and 58 are set to 0. When DST is in effect, bits 57 and 58 are set to 1. On the day of a change from ST to DST bit 57 changes from 0 to 1 at 0000 UTC, and bit 58 changes from 0 to 1 exactly 24 hours later. On the day of a change from DST back to ST bit 57 changes from 1 to 0 at 0000 UTC, and bit 58 changes from 1 to 0 exactly 24 hours later.

Figure 2.6 shows one frame of the time code. The six position identifiers are labeled as P0, P1, P2, P3, P4, and P5. The minutes, hours, days, year, and UT1 sets are marked by brackets; with the weighting factors printed below the bits. Wide pulses represent 1 bits and narrow pulses represent 0 bits. Unused bits are set to 0. The decoded UTC at the start of the frame is 2001, 258 days, 18 hours, and 42 minutes. Since the UT1 correction is –0.7 s, the decoded UT1 is 2001, 258 days, 18 hours, 41 minutes, 59.3 s.

WWVB Coverage Area

The propagation characteristics of LF radio waves make them well suited for time and frequency transfer. At these longer wavelengths, losses in the Earth's surface are low. Thus, the ground wave can travel well for thousands of kilometers and moderate amounts of transmitted power can cover large portions of a hemisphere.

Figures 2.7 and 2.8 show the estimated coverage area of WWVB during the daytime and nighttime hours in the Fall season (October). The dark color indicate areas where signal levels are estimated to be 100 microvolts per meter (μV/m) or greater. Table 2.4 provides a rough estimate of the expected seasonal signal strength at six different locations.

TABLE 2.4 - ESTIMATED SEASONAL SIGNAL STRENGTH OF WWVB, μV/M

Season	UTC	Cutler, Maine	Honolulu	Mexico City	Miami	San Diego	Seattle
Winter	0000	220	3.2	180	180	180	250
Winter	0400	220	125	560	560	1000	560
Winter	0800	220	320	560	560	1000	560
Winter	1200	320	320	560	560	1000	560
Winter	1600	32	3.2	180	100	180	250
Winter	2000	32	3.2	180	100	180	250
Spring	0000	25	3.2	180	100	180	250
Spring	0400	250	32	560	180	1000	560
Spring	0800	250	400	560	180	1000	560
Spring	1200	40	400	320	100	1000	560
Spring	1600	32	3.2	180	100	180	250
Spring	2000	32	3.2	180	100	180	250
Summer	0000	32	3.2	180	100	180	250
Summer	0400	250	8	560	560	1000	560
Summer	0800	250	400	560	560	1000	560
Summer	1200	32	100	180	100	560	320
Summer	1600	32	3.2	180	100	180	250
Summer	2000	32	3.2	180	100	180	250
Fall	0000	125	3.2	180	56	180	250
Fall	0400	250	180	560	500	1000	560
Fall	0800	250	100	560	500	1000	560
Fall	1200	12	100	560	18	1000	560
Fall	1600	32	3.2	180	100	180	250
Fall	2000	32	3.2	180	100	180	250

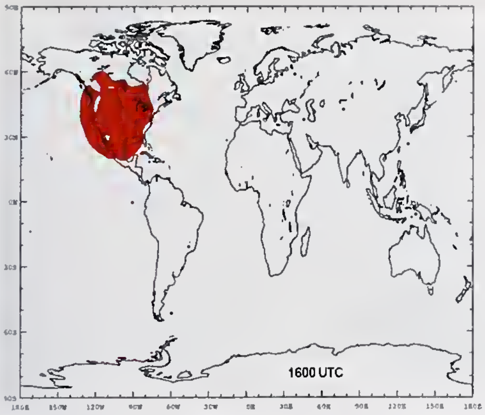

Figure 2.7. Daylight Coverage Area

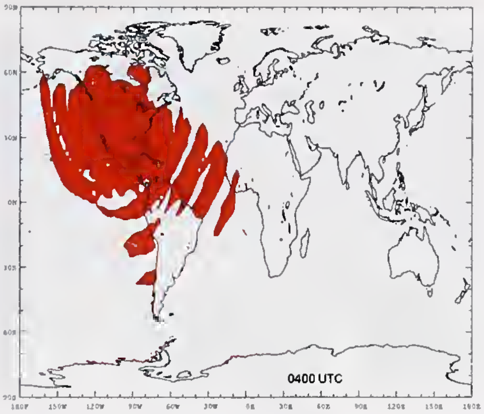

Figure 2.8. Nighttime Coverage Area

WWVB Receiving Equipment and Applications

WWVB receivers are used to control digital and analog wall clocks, desk clocks, travel alarms, clock radios, and wristwatches. New applications for WWVB receivers are found almost daily, and millions of units have been sold.

The simple WWVB receivers share several common characteristics. The receiver usually consists of a single integrated circuit that amplifies and demodulates the WWVB signal. A microprocessor (sometimes integrated into the receiver circuit) is often used to digitally process the time code and drive either an analog or digital display. On some models the microprocessor also outputs the time code to a serial interface so it can be read by a computer system.

Figure 2.9. WWVB Receiver Circuit

One major advantage of WWVB is that the signal can be received using an indoor antenna. LF signals have long wavelengths and when they collide with an object, the angle of incidence is very small. This allows much of the signal to penetrate the object it strikes instead of being reflected. The 60 kHz WWVB signal has a wavelength of approximately 5000 m and can penetrate buildings and walls and easily reach indoor antennas. The antennas used are surprisingly simple. One type of antenna often used in WWVB designs is a ferrite loop, similar to those found inside an AM radio. This antenna consists of a ferrite (a grayish-black metal) bar wrapped with a coil of fine wire. The length of wire and the way it is positioned and wrapped on the bar determine how well the antenna works. The goal is to make the antenna electrically resonant at either a quarter or half-wavelength of the 60 kHz carrier frequency. For the purpose of illustration, a WWVB

receiver that was designed to be embedded inside another device is shown in Figure 2.9. The bar at the top of the photograph is a 4 in (10.16 cm) wide ferrite loop antenna, so you can see that the circuit board is just a few centimeters wide and contains just a few components. Obviously, the receivers and antennas used by some products, such as WWVB wristwatches, are much smaller than the one pictured here.

WWVB clocks like those you might find in a home or office are shown in Figure 2.10. These clocks not only keep accurate time, but they automatically adjust for Daylight Saving Time, leap seconds, and leap years. They work by synchronizing an inexpensive quartz oscillator to the WWVB time code. The period of synchronization varies from model to model, but many units synchronize only once every 24 hours; usually during the evening when the signal is strongest. In between synchronizations, time is kept using the quartz oscillator. Typically, the quartz oscillator can maintain frequency to within a few parts per million, so it will take at least two or three days to gain or lose a full second even if WWVB has not been received. Therefore, synchronizing once per day is usually enough to keep a clock's display on the right second. If you live within the coverage area and your WWVB clock is unable to synchronize, it usually means a source of radio interference is near the receiver. Some common culprits are computer monitors (some have a scan rate at or very close to 60 kHz), noisy AC wiring, fluorescent lamps, or nearby power lines, transformers, or radio transmitters.

Figure 2.10. WWVB Radio Controlled Clocks

More expensive WWVB receivers are used for applications that require better performance and reliability. These receivers continually track the signal, and require an outdoor antenna for best results. Figure 2.11 shows a receiver designed to distribute time to other systems, such as communications systems, computers, wall clocks, voice recorders, radio consoles, phone systems, and so on. This type of receiver includes a large digital clock

Figure 2.11. WWVB Time Distribution Receiver

display, and typically outputs a time code in several different formats. Time codes in text and binary format are output in computer readable format using standard serial interfaces such as RS-232 and RS-485. Standard time code formats like those defined by the Inter-Range Instrumentation Group (IRIG) or the National Emergency Number Association (NENA) might also be available. In addition, this type of receiver might include an on time 1 pulse per second signal that can be used as a measurement reference.

Another type of WWVB receiver is designed to work as a frequency standard that can distribute standard frequencies or be used as a reference to calibrate other oscillators. This type of device is known as a *carrier phase tracking receiver*. It disciplines a stable quartz oscillator so that it agrees with the WWVB signal and outputs standard frequencies such as 100 kHz, 1 MHz, 5 MHz, and 10 MHz. The receiver continuously compares its local oscillator to the WWVB signal and makes corrections as necessary. Some receivers designed as frequency standards ignore the time code entirely and do not output time-of-day or an on-time pulse.

WWVB Performance

NIST maintains the time and frequency standards at the WWVB site as closely as possible. The transmitted frequency of WWVB is maintained within a few parts in 10^{13} and time at the station site is kept within 100 ns of UTC(NIST).

The received performance of WWVB depends upon the quality of the received signal, the type of receiver and antenna used, and the distance between your receiving site and the transmitter. Let's look at a few examples of the type of performance you can obtain.

The majority of WWVB users use the station to get time-of-day, using low cost consumer clocks and watches such as those shown in Figure 2.10. The received time is delayed as

it travels along the signal path from the transmitter to your receiver. The longer the path, the greater the delay. Like all radio signals, the WWVB signal travels at the speed of light and the longest possible delay in the continental United States is <15 ms. For most people and most applications, this small amount of delay really doesn't make any difference. For example, if the time displayed by a wall clock or wristwatch is 15 ms late, your eyes won't be able to tell.

If you need more accurate time, you might want to calibrate the path. For example, some WWVB receivers produce a 1 pulse per second (pps) signal. This signal is intended to be on time, or to coincide with the arrival of the UTC second. Receivers that produce 1 pps may have a switch or software setting that allows you to advance the on-time pulse to compensate for the path delay. You can estimate the path delay with software that computes the distance between your receiving site and WWVB (the station's coordinates are listed in Table 2.1), and then calculates the time required for a radio signal to travel that distance. Using this technique, it's possible to keep time within 0.1 ms of UTC.

If you use WWVB for frequency measurements or calibrations, there is no need to estimate or compensate for the path delay. For frequency, the important issue is *path stability*, or the changes in the path delay that occur over time. Part of the signal that leaves the WWVB transmitter travels along the ground (*groundwave*) and another part is reflected from the ionosphere (*skywave*). Groundwave reception provides better results than skywave reception. The reason is simple—the groundwave signal follows a direct route to your receiver, and therefore the path length doesn't change very much.

Since the groundwave doesn't travel as far as the skywave, it might not be possible to receive. The further you are from the transmitter, the more important it is to have a sensitive receiver and a good antenna in order to track the groundwave. If your receiving site is relatively close to the transmitter (<1000 km), the signal should be predominantly groundwave. For longer paths, a mixture of groundwave and skywave is received. And over a very long path, the groundwave might become so weak that it is only possible to receive the skywave. In this instance, the path becomes much less stable.

The characteristics of a LF path also vary at different times of day. For example, during the daylight and nighttime hours the path delay might vary by only a few hundred nanoseconds. However, if the skywave is being received, phase shifts will occur at sunrise and sunset. For instance, as the path changes from all darkness to all daylight, the ionosphere lowers and the path gets shorter. The path length then stabilizes until either the transmitter or receiver enters darkness. At this point, the ionosphere rises and the path gets longer. If the signal becomes weak and the receiver loses its tracking point on the carrier, it often has to find a new cycle of the carrier to track. Therefore, the received phase of WWVB often shifts by a multiple of 16.67 μs, or the period of the 60 kHz carrier, if the signal is weak or noisy.

WWVB receivers designed as frequency standards attempt to stay locked to the 60 kHz carrier as tightly as possible. Receivers that stay locked to the same groundwave

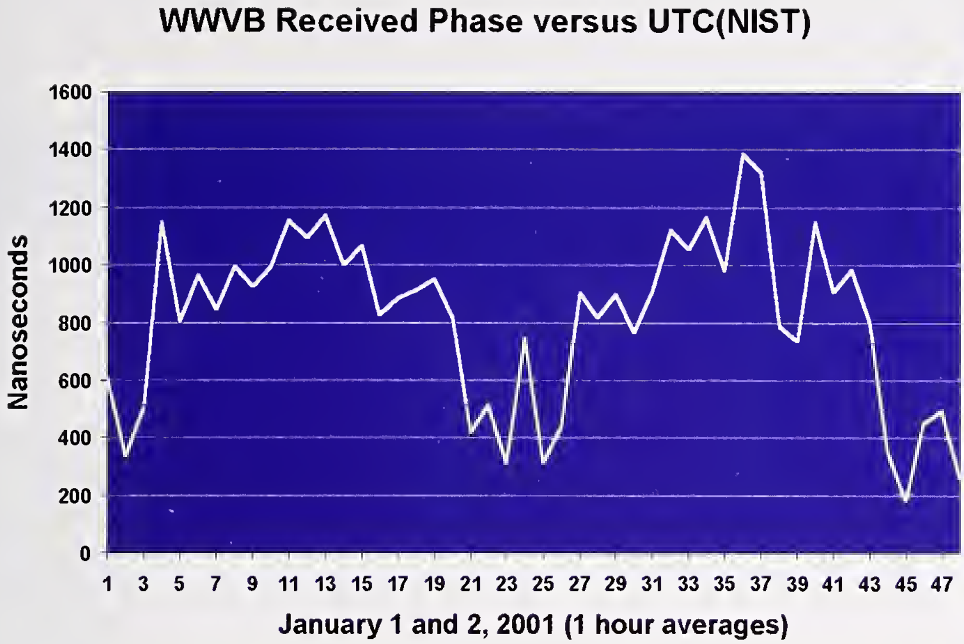

Figure 2.12. WWVB Phase as Received in Boulder, Colorado

cycle at all times can produce frequency traceable to UTC(NIST) with an uncertainty of $< 1 \times 10^{-12}$ when averaged over one or more days. The peak-to-peak variation in the phase is typically about 1 microsecond over 24 hours (Figure 2.12). If the receiver is changing cycles and/or losing lock due to a weak or noisy signal, large phase steps could be introduced and the frequency uncertainty might be 10 to 100 times larger.

The data points shown in Figure 2.12 are one-hour averages so the phase signature (Figure 2.4) has been averaged out. The phase plot shows a diurnal variation due to changes in the path length at sunrise and sunset. Each individual day looks like one "cycle" of the phase plot. This same pattern will repeat itself day after day if the receiver stays locked to the signal.

Chapter 3

Time Signals You Can Hear: NIST Radio Stations WWV and WWVH

The world's most famous time announcements undoubtedly are those broadcast by NIST radio stations WWV and WWVH. Millions of listeners are familiar with these broadcasts, where the announcer states the time in hours, minutes, and seconds "at the tone." These stations operate in the part of the radio spectrum that is properly known as HF (high frequency), but is commonly called shortwave. WWV is located just north of Fort Collins, Colorado, and WWVH is located on the island of Kauai, Hawaii. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz, and WWV also broadcasts on 20 MHz. Both stations can also be heard by telephone. And as we shall see in this chapter, both stations provide much more information than just the time.

The coverage area of the two stations is essentially worldwide on 5, 10, and 15 MHz, although reception might be difficult in some areas, since standard time and frequency stations in other parts of the world use these same frequencies. Both stations send QSL cards confirming reports of long distance reception. WWV has received reports from as far away as the South Pole, and reports from Europe, Asia, and Australia are common. WWVH has received reports from as far away as South Africa, a distance of 19,300 km (12,000 miles) from Hawaii.

WWV and WWVH broadcast the same program on all frequencies, 24 hours a day. At least one of the frequencies should be usable at any given time of day. The most commonly used frequency is 10 MHz, since it is normally usable both during the day and at night. As a general rule, frequencies above 10 MHz work best in the daytime, and the lower frequencies work best at night. The 2.5 MHz broadcasts work best in the area near the stations. For example, the 2.5 MHz WWV broadcast should work well for residents of Colorado and its neighboring states, since propagation is similar to the commercial AM broadcast band.

History and Site Description of WWV

WWV has a long and storied history that dates back to the very beginning of radio broadcasting. The call letters WWV were assigned to NIST (then called the National Bureau of Standards) in October 1919. Although the call letters WWV are now synonymous with the broadcasting of time signals, it is unknown why those particular call letters were chosen or assigned. Testing of the station began from Washington, D.C. in May 1920, with the

broadcast of Friday evening music concerts that lasted from 8:30 to 11 p.m. The 50 W transmissions used a wavelength of 500 m (about 600 kHz, or near the low end of today's commercial AM broadcast band), and could be heard out to about 40 km away from the station. A news release dated May 28, 1920 hinted at the significance of this event:

> *This means that music can be performed at any place, radiated into the air by means of an ordinary radio set, and received at any other place even though hundreds of miles away. The music received can be made as loud as desired by suitable operation of the receiving apparatus. Such concerts are sometimes sent out by the radio laboratory of the Bureau of Standards in connection with trials of experimental apparatus. This music can be heard by anyone in the states near the District of Columbia having a simple amateur receiving outfit. The pleasant evenings which have been experienced by persons at a number of such receiving stations suggest interesting possibilities of the future.*

Interesting possibilities, indeed! Keep in mind that KDKA of Pittsburgh, Pennsylvania, generally acknowledged as the first commercial broadcast station, did not go on the air until November 2, 1920.

On December 15, 1920 the station began assisting the Department of Agriculture in the distribution of market news to farm bureaus and agricultural organizations. A 2 kW spark transmitter and telegraphic code were used to broadcast 500 word reports, called the *Daily Market Marketgram*, on 750 kHz. The operating radius was about 300 km out of Washington. These broadcasts continued until April 15, 1921.

By December 1922, it was decided that the station's purpose would be the transmission of standard frequency signals. The first tests were conducted on January 29th and 30th of 1923, and included the broadcast of wavelengths from 200 to 545 kHz. By May of 1923, WWV was broadcasting frequencies from 75 to 2000 kHz on a weekly schedule. The accuracy of the transmitted frequency was quoted as being "better than three-tenths of one per cent." The output power of the station was 1 kW.

There were numerous changes in both the broadcast schedule, format, and frequency of WWV throughout the 1920's. In January 1931, the station was moved from Washington to the nearby city of College Park, Maryland. A 150 W transmitter operating at 5 MHz was initially used, but the power was increased back to 1 kW the following year. A new device, the *quartz oscillator*, made it possible to dramatically improve the stability of the output frequency of WWV. Quartz oscillators were first used at WWV in 1927, and by 1932 allowed the transmitted frequency to be controlled to less than 2 parts in 10^7.

The station moved again in December 1932, this time to a Department of Agriculture site near Beltsville, Maryland. By April of 1933, the station was broadcasting 30 kW on 5 MHz, and 10 and 15 MHz broadcasts (20 kW output power) were added in 1935. The 5 MHz frequency was chosen for several reasons, including "its wide coverage, its relative freedom from previously assigned stations, and its convenient integral relation with

most frequency standards." The 10 and 15 MHz frequencies were chosen as *harmonics*, or multiples of 5 MHz. WWV continues to use all of these frequencies today, as well as another harmonic (20 MHz), and a sub-harmonic (2.5 MHz).

The Beltsville area was the home of WWV until December 1966 (although the location name for the broadcast was changed to Greenbelt, Maryland in 1961). During the years in Beltsville, many interesting developments took place. A fire destroyed the station in November 1940, but the standard frequency equipment was salvaged and the station returned to the air just five days later using an adjacent building. An act of Congress in July 1941 provided $230,000 for the construction of a new station, which was built 5 km south of the former site and went on the air in January 1943. The 2.5 MHz broadcasts began in February 1944 and have continued to the present day. Transmission on 20, 25, 30, and 35 MHz began in December 1946. The 30 and 35 MHz broadcasts were discontinued in January 1953 and the 25 MHz broadcast was stopped in 1977. With the exception of an almost two-year interruption in 1977 and 1978, the 20 MHz broadcasts have continued to the present day.

Much of the current broadcast format also took shape during the Beltsville years. The 440 Hz tone (A above middle C) was added to the broadcast in August 1936, at the request of several music organizations. Since 1939, 440 Hz (known to musicians as A4 or A440) has been the international standard for musical pitch. The second pulses were added in June 1937, and the geophysical alert messages began in July 1957. And as quartz oscillator technology improved, so did the frequency control of the broadcast. The transmitted frequency was routinely kept within 2 parts in 10^{10} of the national standard by 1958.

WWV's most well known feature, the announcement of time, also began during the Beltsville years. A standard time announcement in telegraphic code was added in October 1945, and voice announcements of time began on January 1, 1950. The original voice announcements were at five-minute intervals. It is interesting to note that WWV continued to broadcast local time at the transmitter site until 1967.

From 1955 to 1958, WWV played a key role in the definition of the atomic second. During this period the United States Naval Observatory (USNO) in Washington, D.C., and the National Physical Laboratory (NPL) in Teddington, United Kingdom made simultaneous common-view measurements of the signals broadcast from WWV. The USNO compared the signal to an astronomical time scale (UT2) and NPL compared the signal to the new cesium standard they had just developed. The data they collected helped the USNO and NPL equate the length of the astronomical second to the atomic second, and led to the atomic second being defined as the duration of 9,192,631,770 cycles of the cesium atom.

In 1966, WWV was moved to its current location, near Fort Collins, Colorado. The LF station WWVB had gone on the air in July 1963 near Fort Collins, and it was decided that WWV would share the same 390 acre (158 hectare) site. The new site was about 80 km from the Boulder laboratories where the national standards of time and frequency were kept. The proximity to Boulder and the use of atomic oscillators at the transmitter site would make it possible to control the transmitted frequency to within 2 parts in 10^{11},

a factor of 10 improvement. Today, the station's frequency is controlled within a few parts in 10^{13}.

At 0000 UTC on December 1, 1966 the Greenbelt, Maryland, broadcast was turned off and the new transmitter at Fort Collins was turned on. In April 1967, the station began broadcasting Greenwich Mean Time (GMT) instead of local time, and began its current format of using Coordinated Universal Time (UTC) in December 1968. The time announcements were made every minute, instead of every 5 minutes, beginning in July 1971.

On August 13, 1991 both WWV and WWVH began broadcasting voice recordings that were digitized and stored in solid state memory devices. Previous voice recordings were played back from mechanical drum recorders, which were more prone to failure. The male voice on WWV was designed to sound like Don Elliot, the station's original announcer. WWVH still uses the voice of its original announcer, Jane Barbe, although the digital storage device has made her voice sound slightly different.

Other new features and programming changes have been added to the WWV broadcast over the past decade, and the current station schedule is described in the remainder of this chapter. A photo of the station is shown in Figure 3.1.

Figure 3.1. Radio Station WWV

History and Site Description of WWVH

WWVH began operation on November 22, 1948 at Kihei on the island of Maui, in the then territory of Hawaii (Hawaii was not granted statehood until 1959). The original station broadcast a low power signal on 5, 10, and 15 MHz. As it does today, the program schedule of WWVH closely follows the format of WWV. However, voice announcements of time were not added to the WWVH broadcast until July 1964.

Figure 3.2. Radio Station WWVH

The original WWVH station site was constantly threatened by an eroding shoreline, and much of the station's equipment and property had been damaged. It was estimated that 75 feet of shoreline were lost in the period from 1949 to 1967. By 1965, the ocean was within a few meters of both the main building and the 15 MHz antenna, and it was obviously necessary to move WWVH to a new location.


Figure 3.3. Aerial View of WWVH Station Site

In July 1971, the station moved to its current location, a 30 acre (12 hectare) site near Kekaha on the Island of Kauai, Hawaii. Photographs of the entrance to WWVH and an aerial view are shown in Figures 3.2 and 3.3.

Station Specifications

WWV and WWVH radiate 10 kW on 5, 10, and 15 MHz. The radiated power is lower on the other frequencies: WWV radiates 2.5 kW on 2.5 and 20 MHz while WWVH radiates 5 kW on 2.5 MHz and does not broadcast on 20 MHz. This information is summarized in Table 3.1.

TABLE 3.1 – SPECIFICATIONS FOR WWV AND WWVH

Characteristics	WWV	WWVH
Date Service Began	March 1923	November 1948
Standard Carrier Frequencies	2.5, 5, 10, 15, & 20 MHz	2.5, 5, 10, & 15 MHz
Power	2.5 kW on 2.5 and 20 MHz, 10 kW on 5, 10, and 15 MHz	5 kW on 2.5 MHz, 10 kW on 5, 10, and 15 MHz

Antennas

The WWV antennas are half-wave vertical antennas that radiate omnidirectional patterns. Since there are five broadcast frequencies, five antennas are in use at all times. Each antenna is connected to a single transmitter using a rigid coaxial line, and the site is designed so that no two coaxial lines cross. Each antenna is mounted on a tower that is approximately one half-wavelength tall. The tallest tower, for 2.5 MHz, is about 60 m tall. The shortest tower, for 20 MHz, is about 7.5 m tall. The 10 m tall tower for the 15 MHz broadcast (with the 122 m tall WWVB towers in the background) is pictured in Figure 3.4.

Figure 3.4. 15 MHz WWV Antenna (WWVB Towers in Background)

The top half of each antenna is a quarter-wavelength radiating element. The bottom half of each antenna consists of nine quarter-wavelength wires that connect to the center of the tower and slope downwards to the ground at a 45° angle. This sloping skirt functions as the lower half of the radiating system and also guys the antenna (Figure 3.5). The WWV antenna coordinates are listed in Table 3.2.

TABLE 3.2 – WWV ANTENNA COORDINATES

Frequency (MHz)	Latitude	Longitude
2.5	40° 40' 55.2" N	105° 02' 31.3" W
5	40° 40' 42.1" N	105° 02' 24.9" W
10	40° 40' 47.8" N	105° 02' 25.1" W
15	40° 40' 45.0" N	105° 02' 24.5" W
20	40° 40' 53.1" N	105° 02' 28.5" W

WWV also has standby antennas that are used only if a primary transmitter or antenna fails. On 2.5, 15, and 20 MHz, these antennas are connected to the standby transmitters. The standby antenna for 15 MHz is an omnidirectional half-wave dipole. Broadband antennas serve as the standby units for 2.5 and 20 MHz. On 5 and 10 MHz, the primary and standby transmitters share the same antenna, and an automated RF switch is used to switch between transmitters if necessary.

The 2.5 MHz antenna at WWVH is nearly identical to its WWV counterpart. However, the 5, 10, and 15 MHz antennas are phased array vertical dipoles. They consist of two half-wave vertical dipoles that are separated by a quarter-wavelength and driven 90° out of phase. These antennas radiate a cardioid pattern with the maximum gain pointed toward the west. Each frequency also has a vertical monopole standby antenna connected to the standby transmitters, in the event that the primary system fails. The WWVH Antenna Coordinates are listed in Table 3.3.

TABLE 3.3 – WWVH ANTENNA COORDINATES

Frequency (MHz)	Latitude	Longitude
2.5	21° 59' 20.9" N	159° 45' 52.4" W
5	21° 59' 10.8" N	159° 45' 44.8" W
10	21° 59' 18.2" N	159° 45' 51.3" W
15	21° 59' 15.3" N	159° 45' 50.0" W

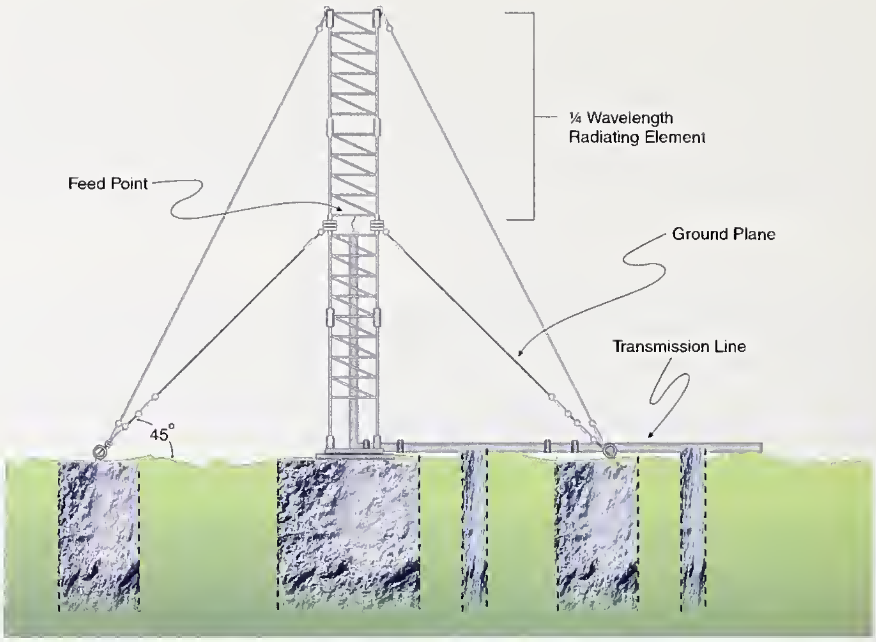

Figure 3.5. Diagram of WWV Antenna

Transmitters

The WWV transmitters consist of two types: plate modulated class C transmitters operating at 10 kW each on 5, 10 and 15 MHz, and class A transmitters operating at 2.5 kW each on 2.5 and 20 MHz. All frequencies have a standby transmitter/antenna system that will automatically begin operating within three minutes of a primary system failure.

WWVH uses class-C plate modulated transmitters on 5, 10, and 15 MHz that operate at 10 kW with 50% efficiency. The 2.5 MHz transmitter is of the class-A type and operates at 5 kW with 20% efficiency. All four frequencies have a backup transmitter/antenna system that will automatically begin transmission within three minutes after the primary system fails. All four of the backup transmitters are 5 kW class-A transmitters, identical to the primary transmitter on 2.5 MHz.

Figure 3.6. WWV Control Room

The signals broadcast by both stations use double sideband amplitude modulation. The modulation level is 50% for the steady tones, 50% for the BCD time code, 100% for the second pulses and the minute and hour markers, and 75% for the voice announcements.

The carrier frequencies and the information modulated on to the carrier are derived from cesium oscillators that are steered to agree with UTC(NIST). Figure 3.6 shows a portion of the equipment in the WWV control room, including the time code generators and cesium oscillators.

Information Transmitted

WWV and WWVH are best known for their audio time announcements, but the stations provide other information as summarized in Table 3.4.

TABLE 3.4 – INFORMATION PROVIDED BY WWV AND WWVH

SERVICE TYPE	INFORMATION PROVIDED
Standard Audio Frequencies	440, 500, & 600 Hz
Time Intervals	Seconds, 10 seconds, minutes, hours.
Time Signals: Voice	Voice announcement is made once per minute
Time Signals: Code	BCD code on 100 Hz subcarrier, 1 pulse/s
Official Announcements	Geoalerts, Marine Storm Warnings, Global Positioning System Status Reports

Figures 3.7 and 3.8 show the hourly program schedules of WWV and WWVH along with station location, radiated power, and details of the modulation.

Time Announcements

Voice announcements are made from WWV and WWVH once every minute. Since both stations can be heard in some areas, a man's voice is used on WWV, and a woman's voice is used on WWVH to avoid confusion. The WWVH announcement occurs first, at about 15 s before the minute. The WWV announcement follows at about 7.5 s before the minute. Though the announcements occur at different times, the tone markers are transmitted at the exact same time from both stations. However, they may not be received at exactly the same instant due to differences in the propagation delays from the two station sites.

Standard Time Intervals

The most frequent sounds heard on WWV and WWVH are the seconds pulses. These pulses are heard every second except on the 29th and 59th seconds of each minute. The first pulse of each hour is an 800 ms pulse of 1500 Hz. The first pulse of each minute is an 800 ms pulse of 1000 Hz at WWV and 1200 Hz at WWVH. The remaining second pulses are short audio bursts (5 ms pulses of 1000 Hz at WWV and 1200 Hz at WWVH) that sound like the ticking of a clock.

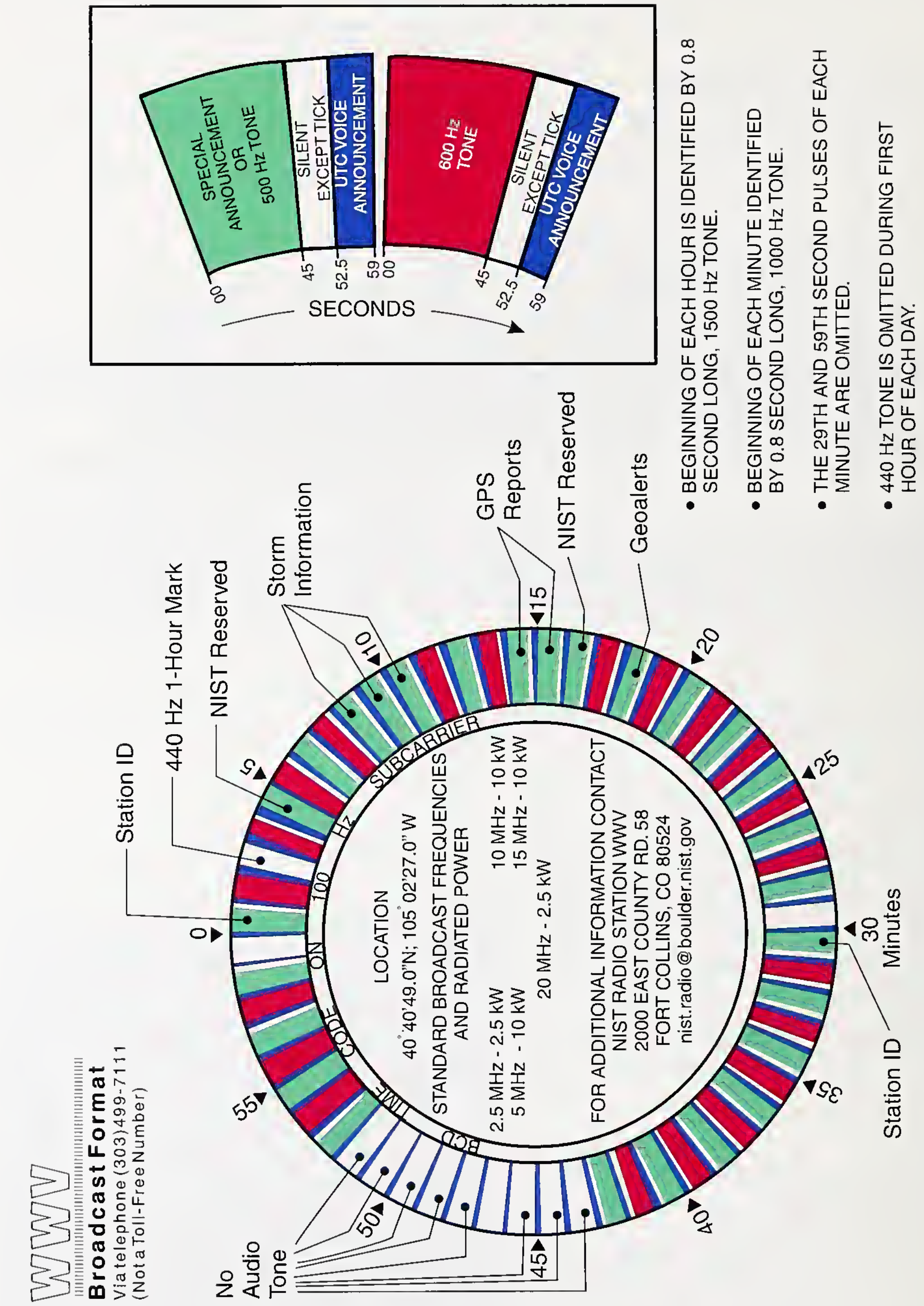

Figure 3.7. WWV Broadcast Format

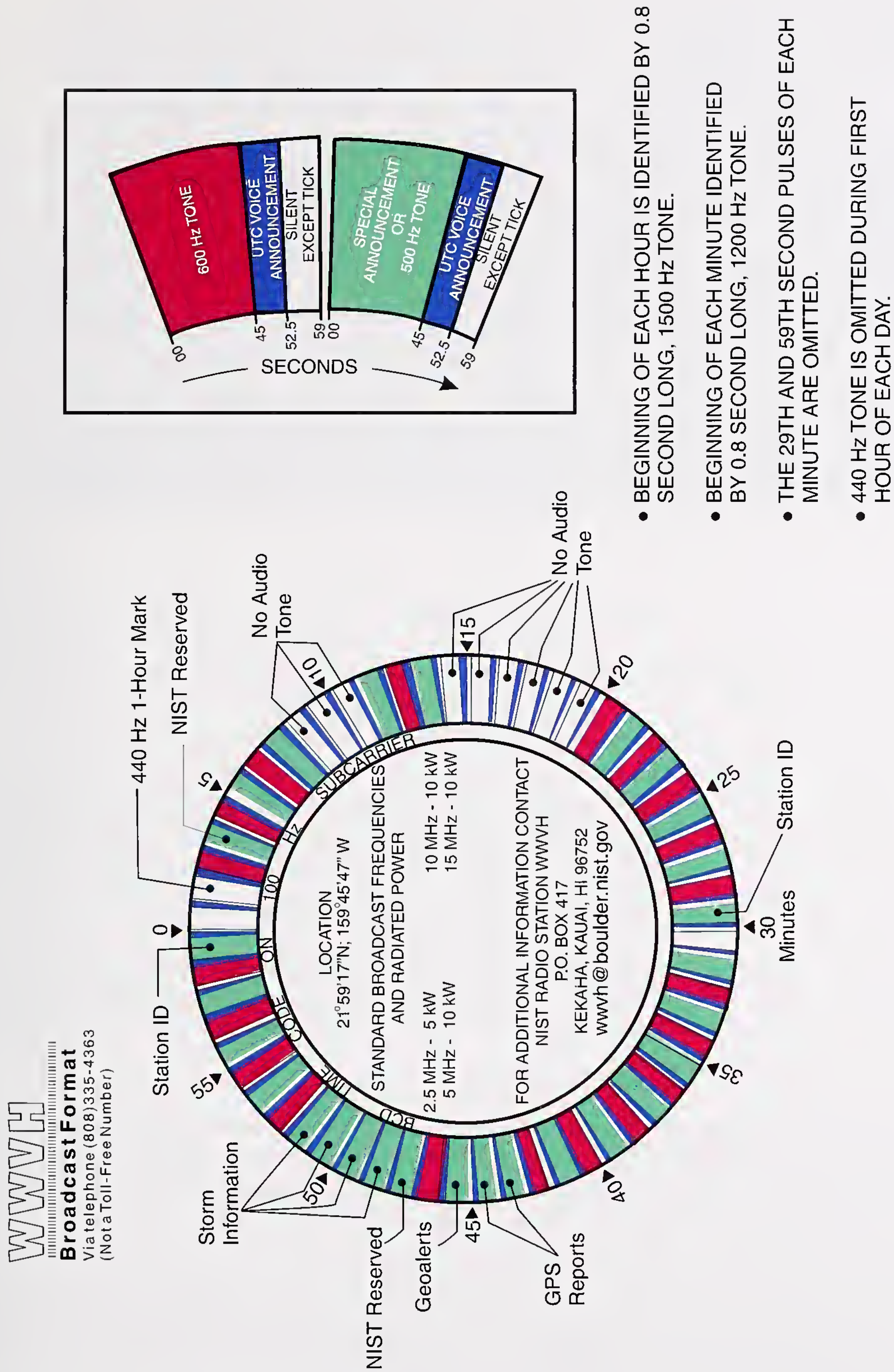

Figure 3.8. WWVH Broadcast Format

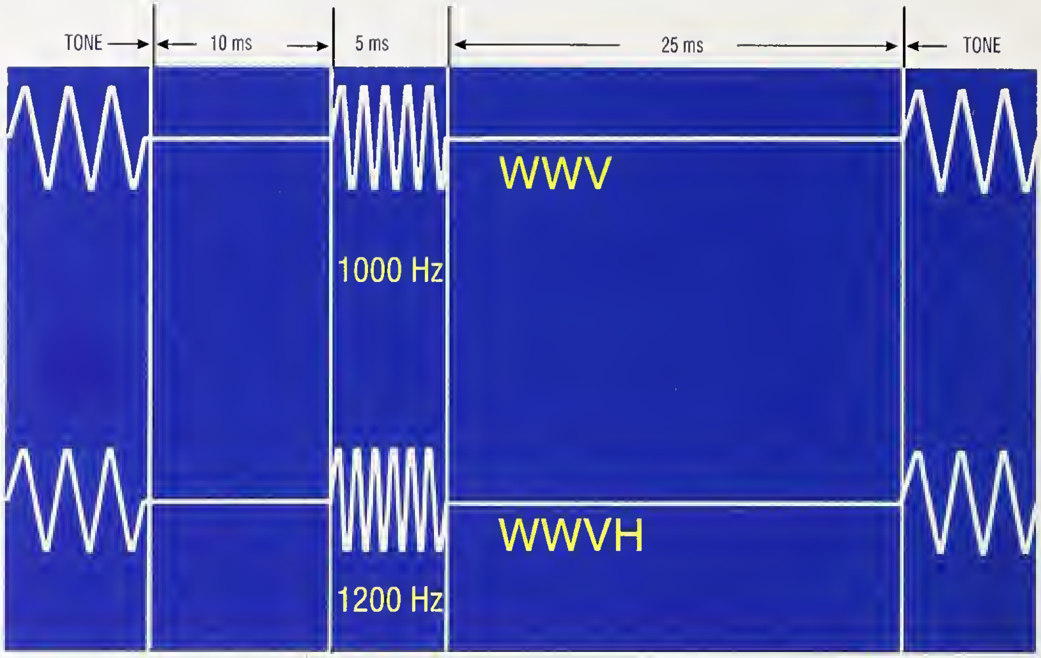

Figure 3.9. WWV and WWVH Second Pulses

Each seconds pulse is preceded by 10 ms of silence and followed by 25 ms of silence. The silence makes it easier to pick out the pulse. The total 40 ms protected zone around each seconds pulse is shown in Figure 3.9.

Standard Audio Frequencies and Silent Periods

In alternate minutes during most of each hour, 500 Hz or 600 Hz audio tones are broadcast. A 440 Hz tone (the musical note A above middle C) is broadcast once each hour. In addition to being a musical standard, the 440 Hz tone provides an hourly marker for chart recorders and other automated devices. The 440 Hz tone is omitted, however, during the first hour of each UTC day. See Figures 3.7 and 3.8 for further details.

The silent periods are without tone modulation. However, the carrier frequency, seconds pulses, time announcements, and the 100 Hz BCD time code continue during the silent periods. In general, one station will not broadcast an audio tone while the other station is broadcasting a voice message.

On WWV, the silent period extends from 43 to 52 minutes after the hour. WWVH has two silent periods; from 8 to 11 minutes after the hour and from 14 to 20 minutes after the hour. Minutes 29 and 59 on WWV and minutes 00 and 30 on WWVH are also silent.

UT1 Correction

UT1 corrections are encoded into the broadcasts by using doubled ticks during the first 16 s of each minute. You can determine the amount of the correction (in units of 0.1 s) by counting the number of doubled ticks. The sign of the correction depends on whether the doubled ticks occur in the first 8 s of the minute or in the second 8 s. If the doubled ticks are in the first 8 s (1 to 8) the sign is positive. If the doubled ticks are in the second

8 s (9 to 16) the sign is negative. For example, if ticks 1, 2, and 3 are doubled, the correction is +0.3 s. This means that UT1 equals UTC plus 0.3 s. If UTC is 8:45:17, then UT1 is 8:45:17.3. If ticks 9, 10, 11, and 12 are doubled, the correction is –0.4 s. If UTC is 8:45:17, then UT1 is 8:45:16.6. If none of the ticks are doubled, then the current correction is 0.

Official Announcements

Announcement segments are available by subscription to other United States government agencies. These segments are used for public service messages up to 45 s long. The accuracy and content of these messages is the responsibility of the originating agency. For information about the availability of these segments, contact the NIST Time and Frequency Division. The announcements that are currently part of the program schedule are described below.

Geophysical Alerts

The National Oceanic and Atmospheric Administration (NOAA) uses WWV and WWVH to broadcast geophysical alert messages that provide information about solar terrestrial conditions. Geophysical alerts are broadcast from WWV at 18 minutes after the hour and from WWVH at 45 minutes after the hour. The messages are less than 45 s in length and are updated every three hours (typically at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC). More frequent updates are made when necessary.

The geophysical alerts provide information about the current conditions for long distance HF radio propagation. The alerts use a standardized format and terminology that requires some explanation. After defining the terminology, we'll look at a sample message.

Solar flux is a measurement of the intensity of solar radio emissions with a wavelength of 10.7 cm (a frequency of about 2800 MHz). The daily solar flux measurement is recorded at 2000 UTC by the Dominion Radio Astrophysical Observatory of the Canadian National Research Council located at Penticton, British Columbia, Canada. The value broadcast is in solar flux units that range from a theoretical minimum of about 50 to numbers larger than 300. During the early part of the 11-year *sunspot cycle*, the flux numbers are low; but they rise and fall as the cycle proceeds. The numbers will remain high for extended periods around sunspot maximum.

Basically, solar flux is measured by counting sunspots, or storms on the surface of the sun. The greater the number of sunspots, the stronger is the ionosphere, the electrified region in the Earth's upper atmosphere. A strong ionosphere means that HF radio signals can be reflected over great distances. Therefore, high solar flux numbers usually, but not always, mean that HF propagation conditions are good. A solar flux figure might be 65 or lower in years of minimum solar activity. In most years, the average solar flux figure falls between 100 and 200.

The A and K indices are a measurement of the behavior of the *magnetic field* in and around the Earth. The *K index* uses a scale from 0 to 9 to measure the change in the horizontal component of the geomagnetic field. A new K index is determined and added to the broadcast every three hours based on magnetometer measurements made at theTable

Mountain Observatory, north of Boulder, Colorado, or an alternate middle latitude observatory. The *A index* is a daily value on a scale from 0 to 400 to express the range of disturbance of the geomagnetic field. It is obtained by converting and averaging the eight, 3 hour K index values. An estimated A index is first announced at 2100 UTC, based on seven measurements and one estimated value. At 0000 UTC, the announced A index consists entirely of known measurements, and the word "estimated" is dropped from the announcement. Table 3.5 shows the relationship between the A and K indices.

TABLE 3.5 – THE RELATIONSHIP BETWEEN THE A INDEX AND K INDEX

A Index	0	3	7	15	27	48	80	140	240	400
K Index	0	1	2	3	4	5	6	7	8	9

The A and K indices are probably the most widely discussed values in radio monitoring circles. If the A index is less than 10 or the K index is around 3, it indicates nearly ideal conditions for HF radio propagation. The lower the figure, the less the signals are absorbed by the Earth's geomagnetic field. Less absorption means that HF signals will travel farther and better.

Solar flux values and the A and K indices can also be used to compute the maximum usable frequency (MUF) and the lowest usable frequency (LUF) for a given time and location. This information is helpful to radio listeners who want to know the best time to tune in hard-to-hear signals.

Space Weather describes the conditions in space that affect earth and its technological systems. Space weather is a consequence of the behavior of the Sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system.

Space weather storms observed or expected to occur are characterized using the NOAA Space Weather scales. The tables below describe the terminology used in the announcements. The descriptor refers to the maximum level reached or predicted. These space weather scales are described in more detail on the NOAA Space Environment Center's web site (http://www.sec.noaa.gov).

TABLE 3.6 – NOAA SPACE WEATHER SCALES

GEOMAGNETIC STORMS	SOLAR RADIATION STORMS	RADIO BLACKOUTS	DESCRIPTOR
G5	S5	R5	Extreme
G4	S4	R4	Severe
G3	S3	R3	Strong
G2	S2	R2	Moderate
G1	S1	R1	Minor

Geomagnetic storm levels are determined by the estimated three hourly Planetary K-indices derived in real time from a network of western hemisphere ground-based magnetometers.

TABLE 3.7 – GEOMAGNETIC STORM LEVELS

PLANETARY K INDICES	GEOMAGNETIC STORM LEVEL
K = 5	G1
K = 6	G2
K = 7	G3
K = 8	G4
K = 9	G5

Solar Radiation storms levels are determined by the proton flux measurements made by NOAA's primary Geostationary Operational Environmental Satellite (GOES).

TABLE 3.8 – SOLAR RADIATION STORM LEVELS

FLUX LEVEL OF >10 MeV PARTICLES	SOLAR RADIATION STORM LEVEL
10	S1
10^2	S2
10^3	S3
10^4	S4
10^5	S5

Radio Blackout levels are determined by the x-ray level measured by the primary GOES satellite.

TABLE 3.9 – RADIO BLACKOUTS

PEAK X-RAY LEVEL AND FLUX	RADIO BLACKOUT LEVEL
M1 and (10^{-5})	R1
M5 and (5×10^{-5})	R2
X1 and (10^{-4})	R3
X10 and (10^{-3})	R4
X20 and (2×10^{-3})	R5

Every geophysical alert consists of three parts as shown in Tables 3.10 and 3.11. Table 3.10 describes the information contained in the geophysical alert. Table 3.11 provides example text from an actual message.

TABLE 3.10 – INFORMATION IN GEOPHYSICAL ALERT VOICE MESSAGE

SECTION	INFORMATION IN VOICE MESSAGE
1	The solar-terrestrial indices for the day: specifically the solar flux, the A index, and the K index.
2	Space weather storms observed during the previous 24 hours. Includes all observed geomagnetic storms, solar radiation storms (proton events) and Radio blackouts (class M1 and greater flares).
3	Space weather expected during the following 24 hours.

TABLE 3.11 – EXAMPLE TEXT FROM ACTUAL GEOPHYSICAL ALERT MESSAGE

SECTION	EXAMPLE OF ACTUAL GEOPHYSICAL ALERT MESSAGE
1	Solar-terrestrial indices for 08 November follow. Solar flux 173 and mid-latitude A-index 14 The Mid-latitude K-index at 1500 UTC on 08 November was 3.
2	Space weather for the past 24 hours has been severe. Solar radiation storm(s) reaching the S4 level is in progress. Radio blackouts(s) reaching the R2 level occurred.
Alternate section 2	No space weather storms have been observed during the past 24 hours.
3	Space weather for the next 24 hours is expected to be severe. Solar radiation storms reaching the S4 level are expected to continue. Radio blackouts reaching the R2 level are expected.
Alternate section 3	No space weather storms are expected during the next 24 hours.

The announcements describe the largest space weather event observed (section 2) or expected (section 3) in the first line of each section. The remaining lines give the type of events and the level observed for each one. In the example above, no geomagnetic storm information is included because none was observed or expected during the period. In the case where none of the three types of events are observed or expected, the announcement would contain section 1, plus alternate section 2 and alternate section 3.

To hear the current geophysical alert message by telephone, dial (303) 497-3235. For more information about these messages, contact: Space Weather Operations, NOAA R/SEC, 325 Broadway, Boulder, CO 80305-3328. Email: swo@sec.noaa.gov Voice: (303) 497-3171.

Marine Storm Warnings

Both WWV and WWVH broadcast marine storm warnings for the ocean areas where the United States has warning responsibility under international agreement. These brief voice messages warn mariners of storm threats present in their areas, and contain information provided by the National Weather Service. Atlantic high seas warnings are broadcast by WWV at 8 and 9 minutes after the hour and an eastern North Pacific high seas warning is broadcast at 10 minutes after the hour. WWVH broadcasts eastern and central North Pacific high seas warnings at 48, 49, 50 and 51 minutes after the hour. Additional segments (at 11 minutes after the hour on WWV and at 52 minutes after the hour on WWVH) are used when conditions are particularly bad.

The storm warnings are based on the most recent forecasts. The forecasts are updated at 0500, 1100, 1700, and 2300 UTC for WWV; and at 0000, 0600, 1200, and 1800 UTC for WWVH. All marine forecasts rely heavily on the Voluntary Observing Ship (VOS) program for obtaining meteorological observations.

A typical storm warning announcement might read like this:

> *North Atlantic weather West of 35 West at 1700 UTC; Hurricane Donna, intensifying, 24 North, 60 West, moving northwest, 20 knots, winds 75 knots; storm, 65 North, 35 West, moving east, 10 knots; winds 50 knots, seas 15 feet.*

For more information about marine storm warnings, write to: National Weather Service, NOAA, 1325 East West Highway, Silver Spring, MD 20910. Or, visit the National Weather Service web page at http://www.nws.noaa.gov.

Global Positioning System (GPS) Status Announcements

The United States Coast Guard sponsors two voice announcements per hour on WWV and WWVH, giving current status information about the GPS satellites and related operations. The 45 s long announcements begin at 14 and 15 minutes after each hour on WWV and at 43 and 44 minutes after each hour on WWVH. For further information, contact the U.S. Coast Guard Navigation Center, 7323 Telegraph Road, Alexandria, VA 22310, or call (703) 313-5900.

WWV/WWVH Time Code

WWV and WWVH each broadcast a binary coded decimal (BCD) time code on a 100 Hz subcarrier. The time code provides UTC information in serial fashion at a speed of 1 bit per second. The information carried by the time code includes the current minute, hour, and day of year. The time code also contains the 100 Hz frequency from the subcarrier. The 100 Hz frequency may be used as a standard with the same accuracy as the audio frequencies.

The time code is sent in binary coded decimal (BCD) format, where four binary digits (bits) are used to represent one decimal number. The binary-to-decimal weighting

scheme is 1-2-4-8. The *least significant bit* is sent first. This is the reverse of the WWVB time code described in Chapter 2. The BCD groups and the equivalent decimal numbers are shown in Table 3.12.

TABLE 3.12 - BCD WEIGHTING SCHEME USED BY WWV AND WWVH TIME CODE

DECIMAL NUMBER	BIT 1 2^0	BIT 2 2^1	BIT 3 2^2	BIT 4 2^3
0	0	0	0	0
1	1	0	0	0
2	0	1	0	0
3	1	1	0	0
4	0	0	1	0
5	0	1	0	1
6	0	1	1	0
7	1	1	1	0
8	0	0	0	1
9	1	0	0	1

Bits are transmitted on the 100 Hz subcarrier using amplitude modulation. A 200 ms pulse (20 cycles of 100 Hz) is used to represent a 0 bit, and a 500 ms pulse (50 cycles of 100 Hz) is used to represent a 1 bit. However, tone suppression deletes the first 30 ms of each pulse. Therefore, 170 ms pulses are recognized as 0 bits, and 470 ms pulses are recognized as 1 bits. The leading edge of each pulse can serve as an on time marker, but due to the tone suppression it actually occurs 30 ms after the start of the second.

WWV and WWVH require 1 minute to send their time code (Figure 3.9). The time code frame contains the minute, hour, day of year, the last two digits of the current year, the UT1 correction, a leap second indicator, and information about daylight and standard time. Two BCD groups are used to express the hour (00 to 23), minute (00 to 59), and year (00 to 99); and three groups are used to express the day of year (001 to 366). The information in the time code refers to the time at the start of the one-minute frame. Seconds are determined by counting pulses within the frame. The individual time code bits are annotated in Table 3.13.

TABLE 3.13 – WWV AND WWVH TIME CODE BITS

BIT NUMBER	BIT DESCRIPTION	BIT NUMBER	BIT DESCRIPTION
0	Frame Reference Bit, Pr (hole)	30	Day of Year, 1
1	Reserved	31	Day of Year, 2
2	DST Indicator	32	Day of Year, 4
3	Leap Second Warning	33	Day of Year, 8
4	Year, 1	34	Reserved
5	Year, 2	35	Day of Year, 10
6	Year, 4	36	Day of Year, 20
7	Year, 8	37	Day of Year, 40
8	Reserved	38	Day of Year, 80
9	Position Marker 1, P1	39	Position Marker 4, P4
10	Minute, 1	40	Day of Year, 100
11	Minute, 2	41	Day of Year, 200
12	Minute, 4	42	Reserved
13	Minute, 8	43	Reserved
14	Reserved	44	Reserved
15	Minute, 10	45	Reserved
16	Minute, 20	46	Reserved
17	Minute, 40	47	Reserved
18	Reserved	48	Reserved
19	Position Marker 2, P2	49	Position Marker 5, P5
20	Hour, 1	50	UT1 Sign
21	Hour, 2	51	Year, 10
22	Hour, 4	52	Year, 20
23	Hour, 8	53	Year, 40
24	Reserved	54	Year, 80
25	Hour, 10	55	DST Indicator
26	Hour, 20	56	UT1 Correction, 0.1 s
27	Reserved	57	UT1 Correction, 0.2 s
28	Reserved	58	UT1 Correction, 0.4 s
29	Position Marker 3, P3	59	Frame Reference Bit, P0

Each time code frame begins with a unique spacing of pulses that mark the start of a new minute. During the first second of the minute, no pulse is transmitted. Since the pulses are already delayed 30 ms by the tone suppression, the UTC minute actually begins 1030 ms (1.03 s) earlier than the first pulse in the frame. For synchronization purposes, position markers lasting for 770 ms are transmitted every 10 s.

A *leap second* indicator is transmitted at second 3. If this bit is high, it indicates that a leap second will be added to UTC at the end of the current month. The bit is set to 1 near the start of the month in which a leap second is added. It is set to 0 immediately after the leap second insertion.

UT1 corrections are broadcast during the final 10 s of each frame. The bit transmitted at second 50 shows if UT1 is positive or negative with respect to UTC. If a 1 is sent, the UT1 correction is positive. If a 0 is sent, the UT1 correction is negative. Bits 56, 57, and 58 form a three-bit BCD group that shows the magnitude of the correction. Since the unit for the UT1 correction is 0.1 s, multiply the BCD group by 0.1 to obtain the correct value. Since only three bits are used, the WWV and WWVH time codes can only transmit UT1 corrections ranging from -0.7 to +0.7 s.

Daylight saving time (DST) and standard time (ST) information is transmitted at seconds 2 and 55. When ST is in effect, bits 2 and 55 are set to 0. When DST is in effect, bits 2 and 55 are set to 1. On the day of a change from ST to DST bit 55 changes from 0 to 1 at 0000 UTC, and bit 2 changes from 0 to 1 exactly 24 hours later. On the day of a change from DST back to ST bit 55 changes from 1 to 0 at 0000 UTC, and bit 2 changes from 1 to 0 exactly 24 hours later.

The year information is transmitted in two different parts of the time code. The last digit of the year is sent using bits 4 through 7. The next to last digit of the year, or the decade indicator, is sent using bits 51 through 54. For example, for the year 2001, bits 4 through 7 will return a decimal value of 1, and bits 51 through 54 will return a decimal value of 0.

Figure 3.10 shows one frame of the time code. The six position identifiers are labeled P0, P1, P2, P3, P4, and P5. The minutes, hours, days, year, and UT1 sets are marked by brackets, with the weighting factors printed below the bits. Wide pulses represent "1" bits and narrow pulses represent "0" bits. Unused bits are set to 0. The decoded UTC at the start of the frame is 2001, 173 days, 21 hours, and 10 minutes. Since the UT1 correction is +0.3 s, the decoded UT1 is 2001, 173 days, 21 hours, 10 minutes, and 0.3 s.

Receiving Equipment

WWV and WWVH can be heard with any *shortwave* receiver. A typical general coverage shortwave receiver provides continuous coverage of the spectrum from about 150 kHz, which is below the commercial AM broadcast band, to 30 MHz. These receivers allow reception of WWV and WWVH on all available frequencies. The best shortwave receivers are often referred to as communications receivers. These receivers are usually designed

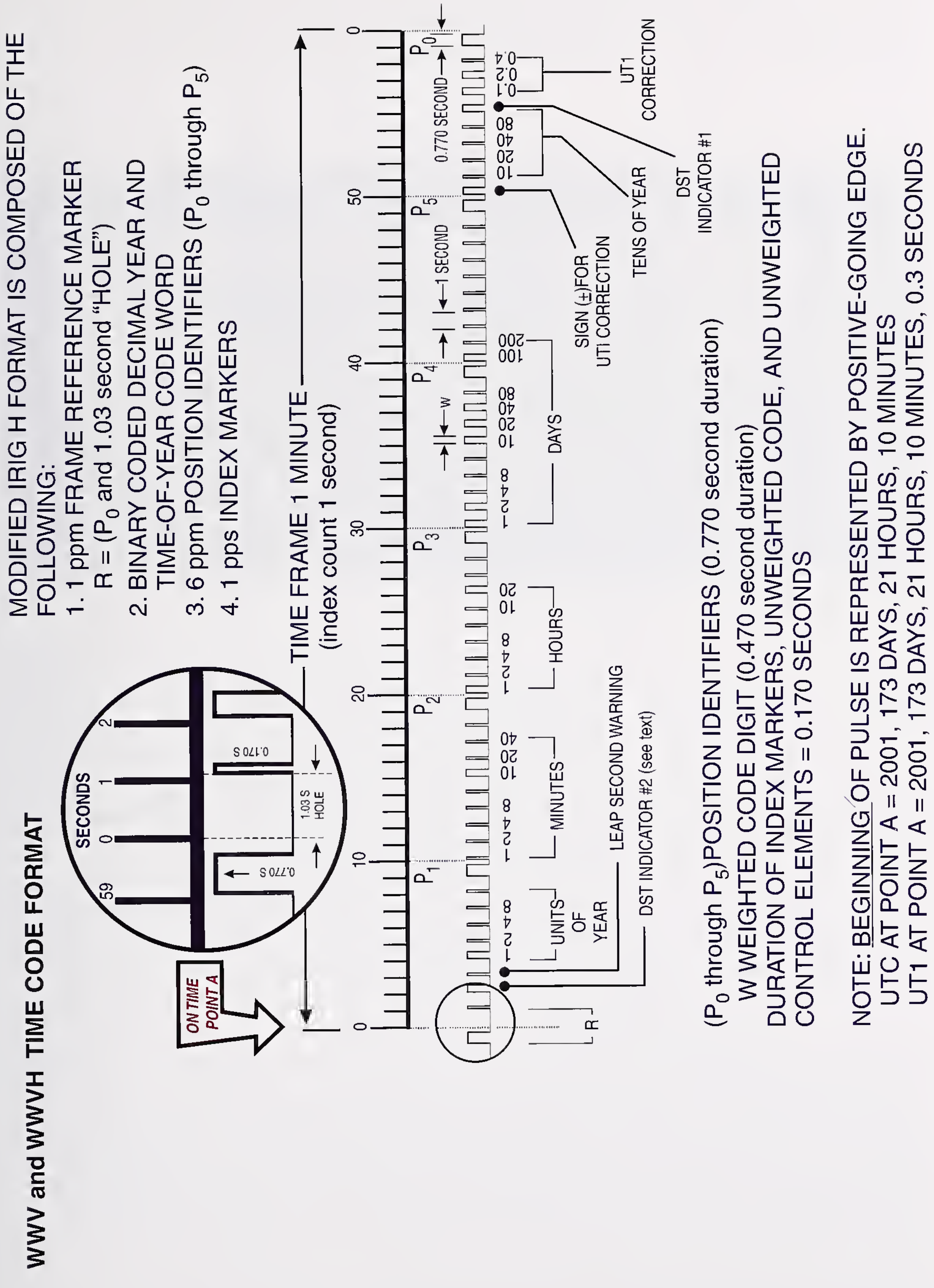

Figure 3.10. WWV and WWVH Time Code Format

as tabletop or rackmount units and are often used by amateur radio operators who operate both a transmitter and receiver. They are designed to work with large outdoor antennas, with quarter-wave or half-wave length dipole antennas often providing the best results. Prices range from less than $500 to more than $5000. A typical communications receiver is shown in Figure 3.11.

Figure 3.11. A HF Communications Receiver

Less expensive shortwave radios are usually portable, and can run off batteries. They typically use a built-in telescopic whip antenna that is less than 1 m long, but most have a connector for an external antenna. Some of the lower cost models only provide coverage of the frequencies commonly used for international broadcasts; typically from about 4 to 12 MHz. These receivers will still provide reception of both WWV and WWVH on 5 and 10 MHz, which are usually the easiest frequencies to receive.

A few low-cost commercially available receivers are dedicated to the task of receiving WWV and WWVH. These receivers might receive only a single frequency, often 10 MHz, and their sole purpose is producing the WWV or WWVH audio.

Receivers that decode and display the time code are also available, but are not nearly as common as their WWVB counterparts. Some units output a time code to a serial interface and/or output a standard time code format defined by the Inter-Range Instrumentation Group (IRIG). In addition, these receivers might include an on time one pulse per second signal for use as a measurement reference. Since it is difficult for a time code receiver to stay locked to a single frequency at all times, these units generally monitor several frequencies and use the one that currently offers the best reception.

Listening to the Signals by Telephone

If you don't have a shortwave receiver, you can still listen to WWV and WWVH by simply making a telephone call. The broadcasts are simulcast by telephone via NIST's

Telephone Time-of-Day Service. The uncertainty of the time announcement depends upon the type of phone call. The time signals are usually delayed by <30 ms if you call from an ordinary telephone (land line) from within the continental United States, and the stability (delay variations) are generally <1 ms during the call. If you are calling from a mobile phone, the delay is often more than 100 ms due to the multiple access methods used to share cell channels. And if you are making an overseas call, your call could be routed through a communications satellite, which might add 250 to 500 ms to the delay.

To hear these broadcasts, dial (303) 499-7111 for WWV and (808) 335-4363 for WWVH. You can listen for about two minutes before your call is disconnected. Please keep in mind that these are not toll-free numbers. Callers outside the local calling area are charged long distance rates.

NIST has provided time signals by telephone for several decades. The WWV number has been available since July 1971, and the Hawaii number has been available since April 1973.

HF Propagation

WWV and WWVH are referred to the primary NIST Frequency Standard and related NIST atomic time scales in Boulder, Colorado. The frequencies *as transmitted* are maintained within a few parts in 10^{13} for frequency and <100 ns for timing with respect to UTC(NIST). In fact, at the transmitter site WWV's frequency is controlled just as tightly as WWVB (Chapter 2). However, the received performance of WWV and WWVH is generally worse than the received performance of WWVB. This is because a HF radio path is much less stable than a LF radio path.

Why is a HF path less stable? Although HF radio propagation is a complex subject, we can provide a simplified explanation here. We mentioned in Chapter 2 that the ground-wave signals from WWVB follow a direct route to your receiver, and therefore the path length doesn't change very much. Other types of radio signals, such as those that originate from satellites, follow even a more direct route. In fact, some signals require *line-of-sight* propagation, which means that nothing can block the path between the receiving antenna and the transmitter. An example would be a GPS satellite antenna, which requires a clear view of the sky.

HF signals are different. They don't have to follow a direct route. In fact, they rely on skywave propagation, which means that they follow an indirect route. HF signals travel past their horizon line, bounce off the ionosphere, and head back down toward Earth and your receiver, which might be on the opposite side of the Earth from the transmitter. This bouncing off the ionosphere is called *refraction*, or *skip*. Sometimes the signals bounce just once off the ionosphere, sometimes they bounce more than once. Each of these bounces or *hops* adds more delay to a timing signal. As you can see, the good news about refraction is that it allows stations to be heard over great distances. The bad news is that refraction makes the signal path (and therefore the amount of the path delay) variable and hard to predict.

The ionosphere generally ranges between 50 and 1200 km above the Earth's surface. The gases in these regions become ionized by the ultraviolet radiation from the Sun. The more radiation, the more ionization occurs. Too much ionization makes the ionosphere too dense to refract signals, and it absorbs signals instead of sending them back to Earth. Not enough ionization means that the ionosphere won't be dense enough to refract or absorb signals. Instead, signals will simply pass through the ionosphere and head off into space.

The ionosphere has several layers that effect HF propagation, specifically the D, E, and F layers. The D layer is usually between 50 and 100 km above the Earth's surface, the E layer is between 100 and 160 km, and the F layer is between 160 and 320 km above the Earth. Each layer reacts differently to different frequencies at different times of day, and even during different seasons of the year. For example, consider that the D layer is very dense during the daytime, and tends to absorb signals below 7 MHz. At night, however, it becomes less dense and is able to refract signals. This means that a 5 MHz signal from WWV probably won't travel very far during the daytime. Those who can receive it during the day are probably close enough to the station to receive the groundwave. At night, however, the 5 MHz signal will refract off the ionosphere and the coverage area will become much larger.

Since the HF radio path delay depends upon so many factors—the frequency used, the time of day, the season, and the ionospheric conditions, to name just a few; it's easy to see that it limits the performance of WWV and WWVH for time and frequency applications. Even so, the signals still meet the requirements for many applications and measurements, as described in the next section.

Applications and Measurement Results

What kind of results can you get using WWV and WWVH? Let's look at the results obtained for several different applications and measurements (summarized in Table 3.13).

Manual Synchronization of a Watch or Clock — Many thousands of people set their clocks or watches to the tones from WWV and WWVH. If you are listening from within the United States either by radio or by telephone, the time should be delayed by <20 ms (less for most listeners) with respect to UTC(NIST). This delay is insignificant when compared to human reaction time, which is no better than 100 ms for most people, and is sometimes several hundred milliseconds or more.

Stop Watch and Timer Calibrations — Calibration and testing laboratories use the audio tones from WWV and WWVH as the reference for stop watch and timer calibrations. These calibrations are actually a time interval measurement, tones from the broadcast are used as signals to start and stop the timer. In between the start and stop tones the timer runs continuously, usually for an interval of at least an hour. When the timer is stopped, the measured time interval on its display is compared to the actual time interval broadcast by the station. The difference between these two values is the time offset, or error of the timer. WWV and WWVH contribute practically zero uncertainty to these measurements. Even though both the start and stop tones are delayed

as they travel to the listener, the difference between the start and stop delays should always be much less than a millisecond. Once again, the largest source of uncertainty is human reaction time.

Tuning a piano — The 440 Hz tones broadcast by WWV and WWVH near the beginning of each hour serve as the ultimate reference for the calibration of pianos and other musical instruments. Since 1939, A440 (the musical note A above middle C at 440 Hz) has been the internationally recognized standard for musical pitch. The piano tuner listens to a standard musical pitch and compares it to the same note on the piano keyboard. The piano is then adjusted (by tightening or loosening strings), until it agrees with the audio standard.

What is the smallest frequency error that a piano tuner can hear? It depends on lots of factors, including the sound volume, the duration of the tone, the suddenness of the frequency change, and the musical training of the listener. However, the *just noticeable difference* is often defined as 5 cents, where 1 cent is 1/100 of the ratio between two adjacent tones on the piano's keyboard. Since there are 12 tones in a piano's octave, the ratio for a frequency change of 1 cent is the 1200^{th} root of 2. Therefore, to raise a musical pitch by 1 cent, you would multiply by the 1200th root of 2, or 1.000577790. If you do this 5 times starting with 440 Hz, you'll see that 5 cents high is about 441.3 Hz, or high in frequency by 1.3 Hz. Obviously, WWV or WWVH will contribute no discernible uncertainty to these measurements, since their 440 Hz tone should have an error of less than 0.001 Hz.

Keep in mind that the actual piano tuning is generally done with a transfer standard such as a tuning fork or an audio tone generator, since those devices are easy to bring to the piano site and their signals are always available. In other words, if you use a transfer standard, you don't have to wait until the top of the hour to hear the tone. However, the audio from WWV or WWVH is often used as a reference for calibrating the transfer standard.

Calibrating a receiver dial — Radio amateurs and shortwave listening enthusiasts often use WWV or WWVH to calibrate their receiver dial. Receivers are usually tested after they have been turned on for at least an hour, so that their internal oscillator has a chance to stabilize. The calibration method varies for different radios, but the object is always to mix the incoming signal from WWV and WWVH with the signal from the receiver's beat frequency oscillator (BFO). This produces a beat note that sounds like a low frequency whistle. The receiver is tuned to the station, and the dial is moved up or down until the whistle completely goes away, a condition known as *zero beat*. Usually, headphones are used to listen for zero beat, since the receiver's speaker might not be able to produce the low frequency beat note signals. Since a person with average hearing can hear tones down to 20 or 30 Hz, an audio zero beat can resolve frequency within 2 or 3 parts in 10^6 at 10 MHz. To get closer, you can also look at the receiver's signal strength, or S-meter. This meter will fluctuate at its slowest rate as the beat note approaches 0 Hz. It should be possible to obtain a beat note of 1 Hz or less, as indicated by a slow "bobbing" of the S-meter back and forth. Once zero beat is reached, the difference between the receiver's dial reading and the carrier frequency of the radio station shows you the frequency offset

of the radio. For example, if you zero beat the 10 MHz carrier from WWV with a dial reading of 10000.2 kHz, the receiver dial has a frequency offset of 200 Hz, or 2×10^{-5}.

Keep in mind that the precision of these calibrations is often limited by the resolution of the tuner. On some lower cost receivers the tuning resolution is 100 Hz, or even 1 or 5 kHz, so the dial will still appear to be correct even if the BFO has a fairly large frequency offset. More expensive receivers sometimes tune in 1 Hz increments. The uncertainty of WWV and WWVH is small enough to set the BFO of even the best receivers to within 1 Hz at 10 MHz, a frequency offset of 1×10^{-7}.

Frequency Calibrations (zero beat) — There are many variations of the zero beat method used to calibrate oscillators other than the BFO in a communications receiver. One simple method involves placing one end of a piece of insulated wire near the oscillator and the other end near the antenna input of your HF receiver. If the radio is tuned to 10 MHz and the oscillator under test is a 10 MHz oscillator, you should hear a slow pulsing sound (beat note) in addition to the WWV or WWVH audio. By adjusting the oscillator, this pulse should get slower and slower until zero beat is reached and no pulsing is heard. The uncertainty of this method is generally equal to 1 cycle of the carrier frequency, or 1×10^{-7} at 10 MHz. This makes it useful for calibrating oscillators such as those found in low cost frequency counters, signal generators, and other types of test equipment.

Time Synchronization — Some WWV and WWVH receivers are designed or modified to produce a 1 pulse per second (pps) signal. This signal is intended to be on time, or to coincide with the arrival of the UTC second. You can estimate the path delay with software that computes the distance between your receiving site and the station (the station coordinates are listed in Tables 3.2 and 3.3), and then calculates the time required for a radio signal to travel that distance. As we saw earlier, HF radio propagation depends on many factors. Without taking all of these factors into account, it's difficult to estimate the path delay to much better than 1 ms. Therefore, most WWV and WWVH time measurements have an uncertainty of about 1 ms, even if you compensate for the path delay. If you don't compensate for path delay at all, the uncertainty is dependent on your distance from the transmitter. It should be < 15 ms for receivers located in the continental United States or near Hawaii.

Frequency Calibrations (phase comparison) — Better results from WWV and WWVH can be obtained by comparing the received phase of the signal to the oscillator under test, and averaging for one day or longer. To use this method, you need a receiver that brings out an electrical pulse, for example a 1 pps signal referenced to the time code. A 1 pps signal is obtained from the oscillator under test using a frequency divider. The two signals are then compared using a time interval counter. While the receiver is locked to the signal, it should be stable to a few hundred microseconds or less. This translates to an uncertainty of parts in 10^9 when averaged for 24 hours, which is sufficient for measuring the frequency offset of most quartz oscillators. Lower uncertainties (parts in 10^{10}) can be realized by making a single measurement (or a short series of measurements) at the same time each day and then averaging the results over multiple days.

TABLE 3.13 – UNCERTAINTIES OF WWV/WWVH MEASUREMENTS

MEASUREMENT OF APPLICATION	REQUIREMENTS	BEST CASE UNCERTAINTY	LARGEST SOURCE OF UNCERTAINTY	UNCERTAINTY CONTRIBUTED BY WWV OR WWVH
Manual synchronization of a watch or clock	Audio time signal obtained with HF receiver or by telephone	100 ms	Human reaction time	Insignificant
Stop watch and timer calibrations	Audio time signal obtained with HF receiver or by telephone	1×10^{-4} in 10,000 s	Human reaction time	Insignificant
Tuning a Piano	Audio time signal obtained with HF receiver or by telephone	5 cents (~ 0.3%)	Human ear's ability to detect difference between two frequencies	Insignificant
Calibrating a Receiver Dial	HF receiver with beat frequency oscillator and S-meter, headphones	1×10^{-7} (1 Hz at 10 MHz)	Dial resolution of receiver	Insignificant for nearly all receiver calibrations
Frequency Calibrations (zero beat)	HF Receiver, oscillator whose output frequency is a multiple or sub multiple of HF carrier	1×10^{-7} (1 Hz at 10 MHz)	Radio path noise	1×10^{-7} (1 Hz at 10 MHz)
Time Synchronization	HF receiver with output pulse	1 ms	Inability to make good path delay estimate	1 ms
Frequency Calibrations (phase comparison)	HF receiver with output pulse, frequency divider for oscillator under test, time interval counter	Parts in 10^9 in 24 hours	Radio path noise	Parts in 10^9

Chapter 4

Keeping Computers on Time: NIST Computer Time Sychronization Services

Since we rely so heavily on computer systems in our daily lives, it shouldn't surprise you that one of the most common time and frequency applications is the synchronization of computer clocks. At this writing (2001) NIST is handling well over 300 million computer timing requests per day through its Internet Time Service, and this number is expected to become much larger in the coming months and years. This chapter describes the NIST services you can use to synchronize your computer clock. It also describes the nist.time.gov web site, which enables you to view NIST time with your web browser.

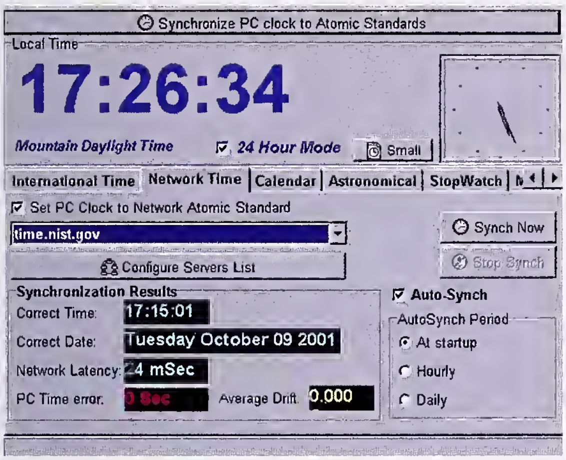

Figure 4.1. ITS Client Software

Internet Time Service (ITS)

The NIST Internet Time Service allows users to synchronize computer clocks via the Internet. The time information provided by the service is directly traceable to UTC(NIST). The service responds to time requests from any Internet client in several formats including the Daytime, Time, and Network Time protocol (NTP). Using the ITS is easy. It requires only an Internet connection and client software compatible with your computer's operating system. A sample ITS software client is shown in Figure 4.1, and software can easily be obtained from a number of publishers.

ITS Servers

The NIST Internet Time Service uses multiple time servers as listed in Table 4.1. NIST maintains a number of time servers. Some are located in Boulder, Colorado, and others reside at other facilities around the country. New servers are added whenever necessary to increase the capacity of the service. Each server is identified by its unique Internet protocol (IP) address. All servers provide the same information, and the same uncertainty relative to UTC(NIST), but some handle more traffic than others and might take longer to handle your request. You can configure your client software so that it points to the server of your choice.

TABLE 4.1 – NIST INTERNET TIME SERVERS

NAME	IP ADDRESS	LOCATION
time-a.nist.gov	129.6.15.28	NIST, Gaithersburg, Maryland
time-b.nist.gov	129.6.15.29	NIST, Gaithersburg, Maryland
time-a.timefreq.bldrdoc.gov	132.163.4.101	NIST, Boulder, Colorado
time-b.timefreq.bldrdoc.gov	132.163.4.102	NIST, Boulder, Colorado
time-c.timefreq.bldrdoc.gov	132.163.4.103	NIST, Boulder, Colorado
utcnist.colorado.edu	128.138.140.44	University of Colorado, Boulder
time.nist.gov	192.43.244.18	NCAR, Boulder, Colorado
time-nw.nist.gov	131.107.1.10	Microsoft, Redmond, Washington
nist1.datum.com	63.149.208.50	Datum, San Jose, California
nist1.dc.glassey.com	216.200.93.8	Abovenet, Virginia
nist1.ny.glassey.com	208.184.49.9	Abovenet, New York City
nist1.sj.glassey.com	207.126.103.204	Abovenet, San Jose, California
nist1.aol-ca.truetime.com	207.200.81.113	True Time, Sunnyvale, California
nist1.aol-va.truetime.com	205.188.185.33	True Time, Virginia

ITS Time Code Formats

Every ITS server is constantly "listening" for one of three different types of timing requests. When it receives one of these requests, it transmits a time code in the requested format. The combination of the timing request and the time code is called a protocol, and each of the three standard timing protocols has been defined by an Internet document called a Request for Comments (RFC). Each protocol is briefly described below. You can refer to the RFC document (available from several Internet sites) if you need more information.

Daytime Protocol (RFC-867)

This protocol is widely used by small computers running MS-DOS, Windows, and similar operating systems. The server listens on port 13, and responds to requests in either tcp/ip or udp/ip formats. The standard does not specify an exact format for the Daytime Protocol, but requires that the time be sent using standard ASCII characters. NIST chose a time code format nearly identical to the one used by its older dial-up Automated Computer Time Service (ACTS) shown in Table 4.3, except that a health digit (H) replaces the UT1 correction, and the time is sent 50 ms (as opposed to 45 ms) early. The health digit indicates the health of the server. If H = 0, the server is healthy. If H = 1, then the server is operating properly but its time may be in error by up to 5 s. This state should change to fully healthy within 10 min. If H = 2, then the server is operating properly but its time is known to be wrong by more than 5 s. If H = 4, then a hardware or software failure has occurred and the amount of the time error is unknown.

Unlike the Time protocol and NTP (described below), the Daytime protocol is not a universal standard. Client software designed to work with NIST's version of the Daytime protocol won't necessarily work with other versions, and vice versa. In contrast, NTP client software should be compatible with all NTP servers.

Time Protocol (RFC-868)

No longer widely used, this simple protocol returns a 32-bit unformatted binary number that represents the time in UTC seconds since January 1, 1900. The server listens for Time Protocol requests on port 37, and responds in either tcp/ip or udp/ip formats. Conversion to local time (if necessary) is the responsibility of the client program. The 32-bit binary format can represent times over a span of about 136 years with a resolution of 1 s. There is no provision for increasing the resolution or increasing the range of years.

The strength of the time protocol is its simplicity. Since many computers keep time internally as the number of seconds since January 1, 1970 (or another date), converting the received time to the necessary format is often a simple matter of binary arithmetic. However, the format does not allow any additional information to be transmitted, such as advance notification of leap seconds or Daylight Saving Time, or information about the health of the server.

Network Time Protocol (RFC-1305)

The Network Time Protocol (NTP) is the most complex and sophisticated of the time protocols, and the one that provides the best performance. Large computers and workstations often include NTP software with their operating systems. The client software runs continuously as a background task that periodically gets updates from one or more servers. The client software ignores responses from servers that appear to be sending the wrong time, and averages the results from those that appear to be correct.

Many of the available NTP software clients for personal computers don't do any averaging at all. Instead, they make a single timing request to a signal server (just like a Daytime or Time client) and then use this information to set their computer's clock. The proper name for this type of client is SNTP (Simple Network Time Protocol).

The NIST servers listen for a NTP request on port 123, and respond by sending a udp/ip data packet in the NTP format. The data packet includes a 64-bit timestamp containing the time in UTC seconds since January 1, 1900 with a resolution of 200 ps.

ITS Performance

The uncertainty of Daytime, Time, and SNTP time clients is usually <100 ms, but the results can vary due to the Internet path, and the type of computer, operating system, and client software. In extreme cases, the uncertainty might be 1 s or more. The uncertainty of a continuously running NTP client is often <10 ms.

Automated Computer Time Service (ACTS)

Although the great majority of computer clocks are now synchronized via the Internet, some applications still require an accurate timing signal that can be obtained over an ordinary telephone line using an analog modem. The Automated Computer Time Service (ACTS) is provided by NIST to satisfy those requirements. Using ACTS requires a computer, an analog modem, and some simple software. When a computer connects to ACTS by telephone, it receives an ASCII time code. The information in the time code is then used to set the computer's clock.

You can connect to ACTS using either a Colorado or Hawaii phone number as shown in Table 4.2.

TABLE 4.2 – ACTS INFORMATION

PHONE NUMBER	LOCATION	PHONE LINES	CAPACITY (CALLS PER DAY)
(303) 494-4774	NIST, Colorado	24	60,000
(808) 335-4721	WWVH, Hawaii	4	10,000

ACTS Time Code

ACTS works at speeds up to 9600 baud with 8 data bits, 1 stop bit, and no parity. To receive the full time code, you must connect at a speed of at least 1200 baud. The full time code is transmitted every second and contains more information than the 300 baud time code, which is transmitted every 2 seconds and omits the MJD and DUT1 information. The full time code is described in Table 4.3 and looks like this:

JJJJJ YY-MM-DD HH:MM:SS TT L DUT1 msADV UTC(NIST) OTM

TABLE 4.3 - THE ACTS TIME CODE

TIME CODE	DESCRIPTION
JJJJJ	The Modified Julian Date (MJD). The MJD is the last five digits of the Julian Date, which is the number of days since January 1, 4713 B.C. To get the Julian Date, add 2.4 million to the MJD.
YY-MM-DD	The last two digits of the year, the month, and the current day of month.
HH:MM:SS	The time in hours, minutes, and seconds. The time is always sent as Coordinated Universal Time (UTC). An offset needs to be applied to UTC to obtain local time. For example, Mountain Time in the United States is 7 hours behind UTC during Standard Time, and 6 hours behind UTC during Daylight Saving Time.
TT	A two digit code (00 to 99) that indicates whether the United States is on Standard Time (ST) or Daylight Saving Time (DST). It also indicates when ST or DST is approaching. This code is set to 00 when ST is in effect, or to 50 when DST is in effect. On the day of the transition from DST to ST, the code is set to 01. On the day of the transition from ST to DST, the code is set to 51. The client software is responsible for implementing the change at 2 a.m. on the day of the transition. During the month of the transition, the code is decremented every day until the change occurs. For example, October is the month of the transition (in the United States) from DST to ST. On October 1, the number changes from 50 to the actual number of days until the time change. It will decrement by 1 every day, and reach 01 on the day of the transition. It will be set to 00 the day after the transition, and will remain there until the following April.
L	A one-digit code that indicates whether a leap second will be added or subtracted at midnight on the last day of the current month. If the code is 0, no leap second will occur this month. If the code is 1, a positive leap second will be added at the end of the month. This means that the last minute of the month will contain 61 seconds instead of 60. If the code is 2, a second will be deleted on the last day of the month.
DUT1	A correction factor for converting UTC to UT1. It is always a number ranging from –0.8 to +0.8 seconds. This number is added to UTC to obtain UT1.
msADV	The number of milliseconds that NIST advances the time code. It is originally set to 45.0 ms. If you return the on-time marker (OTM) to the ACTS server, it will change to reflect the actual one way path delay.
UTC(NIST)	A label that indicates that you are receiving Coordinated Universal Time (UTC) from the National Institute of Standards and Technology (NIST).
OTM	OTM (on-time marker) is an asterisk (*). The time values sent by the time code refer to the arrival time of the OTM. In other words, if the time code says it is 12:45:45, this means it is 12:45:45 when the OTM arrives.

Since the OTM is delayed as it travels from NIST to your computer, ACTS sends it out 45 ms early. This always removes some of the delay. Better results are possible if the user's software returns the OTM to ACTS after it is received. When the OTM returns, ACTS measures the amount of time it took for the OTM to go from ACTS to the user and back to ACTS (round trip path delay). By dividing the round trip path delay by 2, ACTS obtains the one-way path delay. ACTS then advances the OTM by the one-way path delay and the OTM changes from an asterisk to a pound sign (#). When the # sign appears, the time code is synchronized to UTC(NIST) with an uncertainty of <15 ms.

Figure 4.2. nist.time.gov Web Site

nist.time.gov Web Site

If you point your web browser to http://nist.time.gov, you'll see a digital clock display that displays UTC(NIST), or the local time for the United States time zone that you select (Figure 4.2). Although the site can't set your computer's clock, it's useful for manually setting a clock or watch to NIST time. The estimated uncertainty of the display is shown on screen. The uncertainty is typically less than 1 s, and usually within 0.5 s of UTC(NIST).

One of the most popular United States government web sites, nist.time.gov currently (2001) receives millions of timing requests per month. It uses the Internet Time Service as its timing reference, so the time display is generally very accurate. However, keep in mind that it should be used as a time-of-day service only. It should not be used to measure frequency or time interval, nor should it be used to establish traceability to NIST.

Chapter 5

Remote Calibration Services

The services described in the previous chapters consist of signals broadcast by NIST for use as time and frequency references. These signals are provided free of charge as a service of the United States government and meet the needs of most users. However, some of the nation's calibration and testing laboratories require smaller measurement uncertainties. For these organizations, NIST offers a remote calibration service on a paid subscription basis that automates the process of establishing traceability to UTC(NIST).

NIST Frequency Measurement and Analysis Service

The NIST Frequency Measurement and Analysis Service (FMAS) was designed to make it easy for a customer to measure and calibrate any quartz, rubidium, cesium, or hydrogen maser frequency standard in their own laboratory, without sending the device to NIST for calibration. The service can measure any frequency from 1 Hz to 120 MHz in 1 Hz increments. This means it can measure standard output frequencies such as 5 and 10 MHz, telecommunication frequencies such as 1.544, 2.048, and 51.84 MHz, and even 1 Hz timing pulses. As many as five devices can be measured and calibrated at once, even if all five have different output frequencies. The FMAS uses Global Positioning System (GPS) signals as its reference frequency and will work anywhere on Earth. All measurements are made automatically, and are traceable to NIST at an uncertainty of 2×10^{-13} per day.

Subscribers to the NIST service receive a complete frequency measurement system that includes everything needed to make traceable frequency measurements. Once the system is installed, customers simply plug in the frequency standards they want to measure, and connect the system to either a dedicated phone line or Internet connection. This allows NIST personnel to remotely access the system, verify and analyze the data, and quickly troubleshoot any problems that may occur. The GPS signals provide traceability to NIST, since the same GPS signals received by subscribers are received at NIST and compared to the national frequency standard. The GPS receiver is software controlled and requires no operator attention. The customer is required to mount a small antenna in a location with a clear view of the sky. Figure 5.1 shows a two-week measurement of a hydrogen maser made at a customer's location using the FMAS.

NIST completely supports each FMAS customer. When enhancements to the software are developed, NIST installs them for the customer remotely. If any hardware component

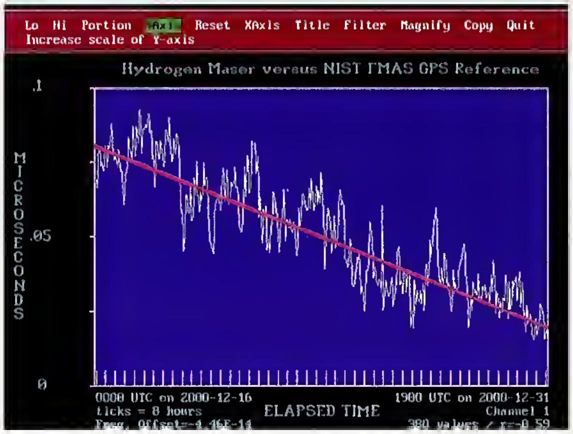

Figure 5.1. Sample FMAS Screen Display

fails, NIST replaces it immediately using an overnight delivery service. Each subscriber receives a monthly calibration report prepared by NIST personnel. The calibration report documents that the customer's primary standard is traceable to UTC(NIST). It includes a graph of the performance of the customer's standard and a statement of measurement uncertainty. The FMAS specifications are listed in Table 5.1.

The FMAS complies with the requirements of NVLAP (National Voluntary Laboratory Accreditation Program). Subscribers to the service who seek accreditation in the frequency calibration field can reduce or eliminate the proficiency testing and on-site assessment fees charged by NVLAP.

NIST offers the FMAS as part of its calibration program. The service identification number is 76100S. For more information, including pricing and delivery, visit the Time and Frequency Division web site at http://www.boulder.nist.gov/timefreq.

TABLE 5.1 – SPECIFICATIONS FOR NIST FMAS

FMAS	SPECIFICATION
Measurement Channels	Up to five frequency standards can be calibrated at one time. The FMAS accepts any input frequency from 1 Hz to 120 MHz in 1 Hz increments.
Measurement Resolution	<30 ps
Frequency Uncertainty using GPS	2×10^{-13} (24 h averaging time)
Relative Frequency Uncertainty without GPS (oscillator to oscillator comparisons)	2×10^{-15} (24 h averaging time)

Acknowledgments

The NIST time and frequency services described in this booklet would not be possible without the continuous efforts of a dedicated technical staff that is responsible for their development, operation, and maintenance. Thanks are due to Matt Deutch, the engineer-in-charge at WWV and WWVB; Dean Okayama, the engineer-in-charge at WWVH; and Judah Levine, who single handedly created the ITS and the current version of ACTS. Thanks are also due to Don Sullivan, the Chief of the Time and Frequency Division; John Lowe, the Services Group Leader; Andrew Novick, radio station staff members Douglas Sutton, Glenn Nelson, Bill Yates, Judy Foley, Don Patterson, Ernie Farrow, and Adele Ochinang. Since time and frequency services at NIST have such a long history, many retired NIST employees obviously made great contributions during their careers. Those I have had the pleasure to know and learn from include Wayne Hanson, Dick Davis, Roger Beehler, Chuck Snider, Joe Cateora, Jim Jespersen, and Al Clements. And finally, I would like to offer a special thank you to retired NIST engineer George Kamas for the many hours that we spent together early in my career, as he patiently and generously shared his knowledge of time and frequency metrology.

Michael A. Lombardi, NIST

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